STUDIES ON LUCERNE FLEA, *Sminthurus viridis* (L.) (COLLEMBOLA : SMINTHURIDAE) AND OTHER COLLEMBOLA IN THE TASMANIAN CULTURE STEPPE

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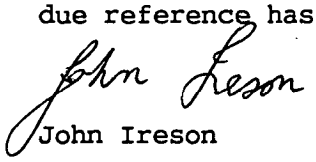

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ABSTRACT

Studies on the lucerne flea, Sminthurus viridis (L.) and other Collembola of the Tasmanian culture steppe covered two main aspects. These were (i) investigations into the biological control of S. viridis in pasture with particular reference to mite predators and (ii) the identification, distribution, phenology and pest status of other Collembola inhabitating the culture steppe, particularly the species of pastures and field crops.

(i) Biological control of S. viridis

Surveys of the distribution of S. viridis and the predatory bdellid mite, Bdellodes lapidaria (Kramer) showed that the mite was uncommon in parts of north-west Tasmania where the pest status of S. viridis was high. Additional investigations at monitored sites in north-west Tasmania where B. lapidaria was present failed to indicate any significant predator-prey relationship between B. lapidaria, S. viridis or other surface-active Collembola. Data obtained on the distribution and phenology of other species of predatory mites from the families Bdellidae, Parasitidae and Anystidae also provided no evidence that any of these were having a significant impact on S. viridis populations. The poor control of S. viridis by established predators led to the initiation of a programme to introduce another predator of S. viridis, the bdellid Neomolgus capillatus (Kramer) from Europe. The predator was successfully established in north-west Tasmania where B. lapidaria is uncommon.

(ii) Identification, distribution, phenology and pest status of Collembola in the Tasmanian culture steppe.

Surveys and population monitoring at selected sites in improved pastures enabled the identification of 51 surface-active species from 6 families and 10 euedaphic species from 3 families. Comparison of the fauna of both the high and low rainfall pasture ecotypes of the State showed that most surface-active species occurred in both ecotypes, although differences between the two were reflected by differences in the adaptability of some species as revealed by variation in their frequencies of occurrence and phenology. Species were shown to have regular annual cycles, however, there was variation in patterns of seasonal periodicity, and temperature and rainfall were shown to have a significant impact on populations.

Surveys of field crops resulted in the identification of 26 surface-active species and only two of these were not collected from pasture. Differing preferences by some species for either the crop or pasture habitat were noted and there was an indication of differing preferences by some species for crops in high and low rainfall areas. Field and laboratory studies on the pest status of Collembola in field crops showed that S. viridis was the most injurious, although field damage by the garden springtail, Bourletiella hortensis (Fitch) and root-feeding Onychiurus spp. was recorded.

A key is given to the species identified in the study including separate keys to Onychiuridae and Hypogastrura spp.

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GENERAL INTRODUCTION

Prior to the commencement of this study, little was known of the Collembola of the Tasmanian culture steppe apart from some studies carried out in the State on the lucerne flea (sometimes referred to as the clover flea), Sminthurus viridis (L.) (Sminthuridae) by Davidson (1934), Evans (1937, 1939) and Wallace and Mahon (1971) because of its pest status, and the identification of about 16 other species recorded by Womersley (1932; 1939).

S. viridis is widely distributed in western Europe and parts of North Africa (Morocco) where it is not generally regarded as a pest (Wallace 1973), but in Australia and South Africa (Walters 1964), it causes serious damage to leguminous crops and pastures, particularly improved pastures based on subterranean clover and lucerne, or white clover and ryegrass.

In Australia, S. viridis was first noted about 1884 in South Australia where it was recorded in large numbers in lucerne around Morphettville (near Adelaide) (Molineau 1897). Wallace (1968) suspected that S. viridis infestations in Australia originated from North Africa or other countries bordering the Mediterranean because the species is well adapted to the Mediterranean-type climate and was probably introduced into Australia in fodder or in damp straw packages.

The first authentic record of economically significant damage by S. viridis was to lucerne paddocks in South Australia (Molineau 1897). Further reports of damage in South Australia were made by Lea (1920, 1922) and Spafford (1921). S. viridis was subsequently recorded from Western Australia in 1910 (Newman 1927a, 1927b) from NSW about 1925 (Anon 1925, cited by Wallace and Mahon 1971) from Tasmania in 1929 (Nicholls 1930) and from Victoria in 1935 (Pescott 1937). In Tasmania, it was not discovered until the end of May 1929 when it was recorded in the north-west at Forth, Lower Gawler and Stanley where it was thought to have been introduced into Tasmania in about 1923 (Nicholls 1930) in improperly cleaned subterranean clover seed purchased from South Australia (Nicholls 1932). Some New Zealand infestations were introduced similarly (Dumbleton 1938) and Walters (1964) attributed the establishment of S. viridis in South Africa to contaminated sub-clover and seed imported from Western Australia.

A report by the Australian Wool Corporation (Anon 1988) ranked S. viridis together with the blue-green aphid (Acyrthosiphon kondoi Shinji) and the red-legged earth mite, Halotydeus destructor (Tucker) as the three most important pests affecting annual pasture legume productivity in Australia, and were stated as responsible for an annual aggregate loss to sheep and wool production in Australia of $228 million. In Tasmania, S. viridis is mainly a pest of cattle grazed perennial pastures in the dairying areas of the north-west and parts of the north-east, (Ireson 1981) with ca 15,000-20,000 ha of pasture being sprayed annually in the

Circular Head district of the north-west for its control. A number of field crops including oil poppies are also frequently reported as being attacked by S. viridis, the damage necessitating control measures (Withecombe 1978). In addition, numerous reports of Collembola other than S. viridis causing damage to the seedling stage of a variety of plants in field crops and home gardens have been recorded by the Tasmanian Department of Agriculture over many years (Ireson unpubl. data), species being associated with damage to both roots and leaves. However, in the past, because the collembolan fauna of the Tasmanian culture steppe was not well known, the identity of species involved has not been recorded and there has often been some doubt as to whether Collembola were actually the primary cause of the damage.

The study reported here had two main objectives. The first was to investigate aspects of the biological control of S. viridis in pastures with particular reference to predatory mites and the second was the identification, distribution, phenology and pest status of the other collembolan species of the Tasmanian culture steppe, with particular reference to the surface-active fauna of pastures and field crops. However, some studies on euedaphic species associated with crop damage were also included.

In this thesis, the term culture steppe is used mainly in the same context as that of Matthews (1976) who defined it as all parts of landscape modified directly by European man, including field crops, improved pastures, settlements, ornamental parks, gardens and roadsides. Although, Matthews excluded 'arboreal monocultures' from his definition, some collection data from orchards and pine plantations are included here.

CHAPTER 1

LITERATURE REVIEW

INTRODUCTION

Collembola, or springtails as they are commonly known, are soft bodied arthropods, the adults of which vary in length from 0.2 - 3mm although a few species may reach sizes up to 10 mm. Species may exhibit uniform colours of white, black, pink or grey or may be mottled and show characteristic colour patterns. Worldwide, over 6000 collembolan species in about 500 genera have been described and it is estimated that about 2000 species occur in Australia (Greenslade in press (a)) and probably 500 of these occur in Tasmania.

Although the lucerne flea, Sminthurus viridis (L.) was first described by Linneaus in 1758, it was only recognised as a pest following its introduction into South Australia when it was recorded damaging lucerne (Molineau 1897). As its pest status increased, it attracted the attention of Australian Entomologists and a number of articles were written about it in Australian Journals, usually giving information on its biology, including a brief description of the species, the type of damage it caused, together with information on its life cycle and control methods (Lea 1922; Newman 1927a, 1927b; Nicholls 1930; Newman and Wormersley 1932; Wormersley 1933a; Currie 1934; Evans 1937, 1943; Norris 1938, Swan 1940; Jenkins and Forte 1948; Johnston 1960). Similar information was published by Davies (1928) in England. More detailed Australian studies on the ecology of S. viridis were published by Holdaway (1927) and this was followed by the studies of Davidson (1931, 1932a, 1932b, 1932c, 1933a, 1933b, 1933c, 1934), Maclagan in England (1932a, 1932b) and Walters (1964) in South Africa. Wallace (1954a, 1954b, 1959, 1963) carried out a series of experiments evaluating insecticides for the control of S. viridis and ecological studies by Wallace (1957, 1967) discussed processes influencing abundance. This included the regulation of populations by density induced mortality (Wallace 1957, 1967) and the relationship between S. viridis and the predatory bdellid mite, Bdellodes lapidaria (Kramer) (Wallace 1967). Womersley (1933a) and Currie (1934) had noted this mite to be an active predator of S. viridis, the latter author producing evidence to suggest that B. lapidaria did have a controlling effect on the pest. The observations of Wallace (1967) subsequently confirmed these conclusions. The presence of an aestivating diapause in the egg stages of both S. viridis and B. lapidaria was also the subject of research (Wallace 1968, 1971). In addition, surveys were carried out to determine the Australian distribution of S. viridis and B. lapidaria (Wallace and Mahon 1971). Surveys were also undertaken in Europe to investigate the assistance of additional predators that would be useful for biological control of S. viridis in Australia. This resulted in the importation and subsequent establishment of another bdellid predator, Neomolgus capillatus Kramer, (Wallace, 1974a, 1974b) together with the anystid mite Anystis salicinus (L.) which was primarily introduced for the control of red-legged earth mite, Halotydeus destructor (Tucker) and blue oat mite, Penthaleus major (Dugès) but which also fed on Collembola (Wallace 1981). The natural

rate of spread of these species is slow and further work on the biological control of S. viridis in Western Australia has only recently re-commenced following the initiation of a redistribution programme which has involved over 170 transfers of both N capillatus and A. salicinus (involving 180,000 individuals) to new sites (Michael 1989).

Apart from S. viridis there has been little information published on the other Collembola inhabiting the culture steppe in Australia. Womersley reviewed the Australian collembolan fauna and listed 48 species other than S. viridis both native and introduced that were injurious. Snowball (1944) discussed the collembolan populations associated with cattle dung and further studies were carried out by Davidson (1979). An account of the biology and systematics of the Australian fauna which included species from the culture steppe was given by Wallace and Mackerras (1970) and recently revised by Greenslade (in press (a)). Detailed studies on the effects of sheep stocking on numbers of Collembola in sown pastures were undertaken by King and Hutchinson (1976) and King et al (1976) and observations on the fauna in natural versus sown fertilized pastures were reported by King et al (1985). Hamilton (1976) gave a brief account of Collembola in home gardens (including control measures) stating that some species were occasional plant pests and others, pests of mushrooms. Clift (1983) discussed the pest status of Collembola in commercial mushroom cultivation. Brief accounts on the biology of Australian Collembola, which also include species from the culture steppe, were given by Wallace and Greenslade (1983) and Greenslade (1984) and a catalogue of the Australian fauna has been completed by Greenslade (in press (b)).

Collembola, being one of the major groups of soil arthropods, have been the subject of much overseas research during the last few decades and a large amount of literature is available on the range of biological studies that have been carried out. General accounts of the bionomics of Collembola are given by Paclt (1956), Christiansen (1964), Butcher et al (1971), Joosse (1981, 1983) and Fjellberg (1985) and the world fauna were indexed by Salmon (1964).

Reviews of the literature on S. viridis have been carried out by Walters (1964) and Dentener (1985). This chapter reviews information on the taxonomy, distribution, biology, pest status and control of S. viridis and is augmented by additional information available on other collembolan species with particular reference to species inhabiting the culture steppe.

GEOGRAPHICAL DISTRIBUTION

(1) General distribution of Collembola

Collembola are ubiquitous, being found in all terrestrial biomes, including mountain tops, polar regions, deserts, caves, marine, fresh water and littoral habitats (Greenslade in press (a)). Many species (eg.

Isotomurus palustris (Mueller)) have a cosmopolitan distribution and in general are more widespread than any other group of arthropods. This may be because they are easily dispersed by air and water currents, by animals or by soil and vegetable matter and also that they are of great antiquity (Hale 1967). A Devonian fossil known from the Rhynie Chert in Scotland, Rhyniella praecursor Hirst and Maulik has morphological features which suggest affinites with the Isotomidae (Greenslade and Whalley 1986) and is the earliest known hexapod. Salmon (1941) postulated a northern European primary evolution for Collembola, with a later tridirectional migration to Africa, North America and Australasia, the worldwide distribution of certain species lending support to such a theory. Maynard (1951) classified species of cosmopolitan distribution into two categories, firstly those which have become distributed with the advent of man and secondly the more primitive species which attained a cosmopolitan status in early geological time; from this latter group it was postulated that various species may have evolved which we now call indigenous. Although factors such as air and water currents may have played important roles in the dispersal of Collembola even in geological eras, the transportation factor during the age of man often makes it difficult to determine whether man has been involved in the introduction of a species. Lindroth (1957) suggested five criteria could be used in trying to separate the elements of the recently introduced fauna from the indigenous fauna of a continent. These were: (i) the historical criterion (tracing historical evidence of the landing of a species), (ii) the geographical criterion (a recently introduced species may have a more localised distribution or be unco-ordinated with the environment, (iii) the ecological criterion (the ecology of a species may indicate its character as a foreigner), (iv) the biological criterion (species not being able to establish in a new habitat until the establishment of their hosts) and (v) taxonomic criteria.

(2) World distribution of S. viridis

S. viridis is of Palaearctic origin (Walters 1964) but has invaded the southern hemisphere and now has a cosmopolitan distribution. The Commonwealth Institute of Entomology (Anon. 1973a) details the known worldwide distribution of S. viridis and provides a distribution map together with the list of countries (and references) where it has been recorded. This includes most European countries (including Iceland), Asia (China, India, Iran, Iraq, Israel, Japan, Pakistan) parts of the U.S.S.R. (European U.S.S.R., Latvia, Lithuania, Ukraine, White Russia), Africa (Algeria, Egypt, Libya, Morocco, South Africa (Cape Province), Tunisia), North America (parts of north-west Canada and Alaska), South America (Argentina, Uruguay) the North and South Islands of New Zealand and Australia.

(3) Distribution of S. viridis in Australia

Details of the distribution of S. viridis in South Australia were given by Holdaway (1927) and Davidson (1932a) and in other Australian States by

Davidson (1934). Wallace and Mahon (1971) compiled a comprehensive list of all known records of S. viridis in Australia and prepared distribution maps following a collecting trip in the winter of 1962 which covered all the southern States of Australia. They showed that the European origin of S. viridis was reflected in its restriction to the southern parts of Australia, particularly in areas with an essentially Mediterranean-type climate apart from a few isolated occurrences in eastern NSW.

(4) Distribution of S. viridis in Tasmania

Records of the occurrence of S. viridis in Tasmania up to 1964 were provided for the survey of Wallace and Mahon (1971) by the Tasmanian Department of Agriculture. Collection localities up to this time were: Bridgewater, Flinders Is., Stanley, Smithton, Irishtown, Forest, Calder, Boat Harbour, Flowerdale, Table Cape, Wynyard, Seabrook, Burnie, Stowport, Gunns Plains, Warringa, Ulverstone, Gawler, Forth, Lillico, Devonport, New Ground, Harford, Moriarty, Northdown, Deloraine, Launceston, Lebrina, Scottsdale, Evandale, Tonganah, Swansea, Rheban, Dunnalley, Dysart, Brighton, Broadmarsh, Old Beach, New Norfolk, Gretna, Geeveston, Barnes Bay (North Bruny Is.) and North Bruny Island.

Additional infestations up to the commencement of this study were recorded at Glendevie (Martyn et al 1969), Kimberley and Pipers River (Martyn et al 1970), Somerset, Triabunna and Woodbridge (Martyn et al 1971), Campbell Town, Moltema, Cressy and Whitemark (Martyn et al 1972); Hayes, Winnaleah and Rocky Cape (Martyn et al 1973), Dulverton, Relbia, Ross, Kempton, Elizabeth Town, Exton, Sheffield, Hagley, Sassafras and the Huon Valley (Martyn et al 1974).

(5) Limits and predictions of the distribution of S. viridis

Maclagan (1932b) attempted to predict the world distribution of S. viridis on the basis of laboratory experiments on the effects of temperature and moisture on development and survival, and charted the geographical limits of existence on a world map. These calculations broke down in areas of high summer rainfall, probably because it was not known that S. viridis produced diapause and non-diapause eggs (Wallace 1968) and that the species could not exist in areas experiencing a combination of high temperatures and high rainfall in summer, unless it were able to produce diapause eggs which would not hatch under those conditions (Wallace and Mahon 1971). Areas of economic significance were predicted on the basis of critical values for S. viridis of 79-152 mm (3.1"-6.0") of rainfall per month, together with a mean monthly temperature ranging between 11 and 14°C. However, Maclagan also did not account for the significance of soil moisture in relation to rainfall and evaporation. Davidson (1934), prepared a series of maps showing the limits of possible distribution of S. viridis in Australia as a series of zones which differed in degree of favourableness, based on climatic data. The ratio of rainfall to evaporation (R/E ratio) was considered to be the best single factor index to moisture conditions at the soil surface

each month and the index was used in Davidson's calculations. It was found that hatching of oversummering eggs takes place when the R/E ratio rises above 1 and that numbers declined at the end of the wet season when the ratio falls below 1. Furthermore, it was shown that the range of mean monthly temperatures best suited for population range increases of S. viridis in Australia was 11-15°C and that the species would not become permanently established in areas where the mean monthly temperature extended to 21°C for 1 month where the R/E ratio was not less than 1. Although Davidson's predictions have proved reasonably accurate, they broke down in the summer rainfall areas of eastern Victoria and New South Wales. Based on a knowledge of the occurrence of diapause eggs in S. viridis and the nutritional requirements for their production, Wallace and Mahon (1971) showed that the 225 mm isohyet for December-March inclusive seemed to define this area with precision. They also showed that the northern inland limit to its distribution agreed closely with the 250 mm isohyet for May-October inclusive.

In the northern hemisphere, surveys by Wallace (1973, 1974b) in Europe showed that the northern distribution limit appeared to lie at about the 63°N latitude at sea level but at lower latitudes at higher altitudes. This corresponded closely with localities in which there were 100 consecutive frost-free days during summer (i.e. days when the mean temperature rose above 10°C). This was considered by Wallace (1973) to be the time interval necessary to ensure that at least one generation of S. viridis can be completed before temperatures returned to lower levels. The southern distribution limits in Spain and Morocco corresponded with the 250 mm isohyet for the period November-April inclusive and was similar to the northern distribution limit for the species in Australia.

TAXONOMY

Greenslade (in press (a)) has re-classified the Collembola using additions to the classification of Gisin (1960) by Massoud (1967, 1971), Richards (1968), Betsch (1980) and Fjellberg (1980). This latest classification divides the class Collembola into three orders, 2 super-families and 14 families as follows:

CLASS COLLEMBOLA

Order: ARTHROPLEONA
Superfamily: ENTOMOBRYOIDEA
Family: Isotomidae
Entomobryidae
Paronellidae
Cyphoderidae
Oncopoduridae
Tomoceridae
Superfamily: PODUROIDEA
Family: Neanuridae
Odontellidae

Brachystomellidae
Hypogastruridae
Onychiuridae
Order: NEELIPLEONA
Family: Neelidae
Order: SYMPHYLEONA
Family: Sminthuridae
Dicyrtomidae

The orders are distinguished by an elongate body and prognathous head in the Arthropleona and a globular body and a hypognathous head in the Symphypleona. In the Neelipleona, the body is globular and the head hypognathous, but the antennae are reduced and there are no ocelli. Comprehensive keys to the Collembola are given by Stach (1947, 1949, 1954, 1956, 1957), Gisin (1960), Massoud (1967), Richards (1968), Betsch (1980), Christiansen and Bellinger (1980a, 1980b, 1980c, 1981) and Fjellberg (1980) and are amongst the most widely used for the purpose of identification.

S. viridis was first described by Linnaeus from Sweden in 1758. Other descriptions, mainly of the adult stage have been given by various authors including Lubbock (1868, 1873), Lea (1922), Davies (1928), Davidson (1934), Dumbleton (1938), with more detailed taxonomic descriptions being presented by Walters (1964), Lawrence (1966) and a detailed description of the reproductive organs by Betsch-Pinot (1976). The systematic status of S. viridis was reviewed by Walters (1964) and Dentener (1985). 7 species of Sminthuridae, (including S. viridis), were identified at a number of localities in the Tasmanian culture steppe by Womersley (1932). These were included in his review of the Australian fauna (Womersley 1939) in which 16 species (including varieties) of the 48 listed from Tasmania were probably collected from the culture steppe. The actual number collected is uncertain from the literature available as habitats and localities were not always given. These 16 species, together with the collection data provided by Womersley (1932, 1939) are listed in Table 1.1.

Womersley includes amongst these a dark form of B. viridescens as a variety of this species (var. fusca Womersley 1932) and a colour variety of S. viridis (medicaginis) described by Schoett (1917). Although green and yellow colours predominate, S. viridis shows considerable colour variation, the green-yellow form being common in spring and a darker colour form with black and brown markings being common in winter (Swan 1940). Walters (1964) produced evidence that colour variation was not a valid criterion for dividing species into varieties and found that colour variation in S. viridis was apparently determined by environmental factors. This conclusion was reached after laboratory studies and field observations in South Africa indicated that the darkest forms of S. viridis were most abundant during the coldest months and the lightest

Table 1.1 Collembola recorded from the Tasmanian culture steppe by Womersley (1932, 1939).

Species	Locality data
Smithuridae	
Jeannenotia stachi australiensis Betsch and Massoud (recorded as Sminthurides (Stenacidia) violacea Reuter)	Devonport, (Wormersley 1939)
Katianna australis Womersley	Stanley area (Womersley 1932)
Katianna mucina Womersley	Launceston (Trevallyn) (Womersely 1939)
Katianna ornata Wormersley	Tasmania (agricultural areas) (Womersley 1939)
Deuterosminthurus sulphureus meditteraneus Ellis (recorded as Deuterosminthurus bicinctus v. repandus Agren)	Glenorchy (Womersley 1932, 1939)
Prorastriopes quinquefasciatus (Krausbauer) (recorded as Deuterosminthurus cinquefasciatus Krausbauer)	Gawler, Forth area (Womersley 1932, 1939)
Rastriopes obscurus (Womersley) (recorded as Deuterosminthurus obscurus Womersley)	Scottsdale (recorded as attacking the tops of young carrots (Womersley 1932, 1939)
Bourletiella hortensis Fitch	Gawler, Forth, Stanley (Womersley 1932)
Bourletiella viridescens (Stach) (recorded as Bourletiella arvalis v. fusca Womersley)	Stanley, Franklin, Longford, Forth, Gawler and Forest (Womersley 1932)
Sminthurus viridis (L.) (and Sminthurus viridis v. medicaginis Schoett)	Listed as common in Tasmania but no localities given (Womersley 1932, 1939)
Entomobryidae	
Entomobrya atrocincta (recorded as Entomobrya clitellaria Guthrie)	Widespread in all agricultural areas of Australia, occuring in all States (Womersley 1939)

Table 1.1 Collembola recorded from the Tasmanian culture steppe (cont.) by Womersley (1932, 1939).

Species	Locality data
Entomobrya multifasciata (Tullberg)	Common in cultivated areas of all Australian States (Womersley 1939).
Entomobrya unostrigata Stach (recorded as Entomobrya tenuicauda Schoett)	New Town (Womersley 1939)
Isotomidae	
Isotomurus palustris (Mueller)	Common amongst low herbage in pastures in all southern States (Womersley 1939)
Hypogastrura manubrialis (Tullberg) (recorded as Hypogastrura manubrialis v. neglecta Boerner)	New Town (Womersley 1939)

forms were dominant in the warmer months. As dark colours absorb more heat under cold conditions and light colours reflect more heat under warm conditions, body colour may be a significant factor in the regulation of body temperature for S. viridis and other epigaeic species at different times of the year. Studies on the pigmentation of Collembola by Rapoport (1969) showed that their coloration is a result of the interaction of several factors, including temperature (solar radiation, latitude and altitude), rainfall and humidity, type of pigment involved and ground colouration.

Lawrence (1966) in his redescription of S. viridis was unable to separate this species from the closely related Sminthurus nigromaculatus Tullberg, apart from a few obvious differences in colouration. However, the S. viridis complex was further investigated by Wallace (1973) who recognised S. nigromaculatus Tullberg (formerly S. viridis nigromaculatus) and S. marmoratus Stach (formerly S. viridis marmoratus) as distinct species following collections throughout Western Europe and Morocco. Wallace confidently classified S. nigromaculatus as a distinct species on the basis of pigmentation characters which he found consistently different from those of S. viridis and S. marmoratus. He also found that in contrast to the other 2 species S. nigromaculatus fed only on dead plant tissue and had a distribution distinct from S. marmoratus and only slightly overlapped by S. viridis. Although separation of S. viridis from S. marmoratus was found more difficult, Wallace was able to do so mainly on the basis of pigment patterns supported by head and eye-width measurements. S. marmoratus was also found to have an exclusively

Mediterranean distribution.

During my study, colour patterns were often used to distinguish species. However, intraspecific colour variations were noted in S. viridis and amongst other species particularly in the genera Sminthurinus and Katianna. Such variations were considered a response to environmental factors and were usually easily recognised. An overlapping range of the colour characters was often observed in the same population (see Chapter 13).

ANATOMY

Descriptions of the anatomy of Collembola are given by Maynard (1951), Paclt (1956), Wallace and MacKerras (1970) and Christiansen and Bellinger (1980a).

ECOLOGICAL CLASSIFICATION

A number of systems for the ecological classification of Collembola have been developed and these were discussed by Christiansen (1964) who proposed a new classification based on that by Gisin (1943). Christiansen classified the Collembola into 5 main categories (Table 1.2) acknowledging that each was capable of being subdivided and that no category was mutually exclusive as overlap did occur. Although ecological characteristics are accounted for the classification is primarily morphological.

Aitchison (1984) used the terms euedaphic and hemiedaphic (as defined by Christiansen 1964) during studies on the phenology of Collembola from South Central Canada, however, he refers to collembolans on the surface of the litter with long antennae and eight eyes as epedaphic.

LIFE CYCLES

The life cycle of S. viridis has been studied in detail in England (Maclagan 1932a, 1932b), in New Zealand (Dumbleton 1938), in South Africa (Walters 1964) and in Australia (Holdaway 1927; Davidson 1934; Wallace 1967, 1968). There have been no other detailed studies of the life cycle of a collembolan in Australia and the relatively few reported overseas have mainly involved Arthropleona. These include Hypogastrura manubrialis (Tullberg) by Ripper (1930), H. purpurescens (Lubbock) by Strebel (1932), Isotomurus palustris (Mueller) by James (1933), Orchesella cincta (L.) by Lindenmann (1950), H. armata by Britt (1951), Tullbergia krausbaueri (Boerner), Folsomia candida (Willem), Isotoma viridis Bourlet, Neanura muscorum (Templeton) together with 3 Onychiurus spp. by Milne (1960), Isotoma notabilis Schaeffer by Sharma and Kevan (1963a), Folsomia candida (Willem) by Snider (1973) and Snider and Butcher (1973) and H. viatica (Tullberg) by Mertens et al (1983). Apart from S. viridis, the life cycles of other Symphypleona studied include only Sminthurides aquaticus Bourlet (Falkenham 1932) and studies by Blancquaert et al (1981a, 1981b) on embryonal and post-embryonal

development, diapause, and reproduction in S. aquaticus, Arrhopalites sericus Gisin and Sphaeridia pumilis (Krausbauer).

(1) Fertilisation

In most Collembola, sperm is transferred indirectly by placing spermatophores on the substrate (Blancquaert 1981) and mating behaviour, which ensures the take-up of sperm through the genital aperture of the female, is variable. Specific pairing and bodily contact as well as indirect spermatophore transfer without association between partners has

Table 1.2 Ecological classification of Collembola (after Christiansen 1964).

Species category	Characteristics	Normal ecological distribution
Epigaeic	Eight eyes, well pigmented; antennae and furcula long	Plant growth
Hemiedaphic	Antennae moderately long; eyes and pigment well developed	
neustonic	Lamellate mucro; large tarsal claw (unguis) modified	Water surface
normal	Normal mucro; few clavate or pointed tenent hairs	Surface, ground litter
xeromorphic	Normal mucro; cuticle often rigid; numerous clavate tenent hairs	Moss, bark, lichens
Euedaphic	Eyes reduced; antennae short; pigment absent or limited to eyes	Deeper layers of soil, caves, and soil cavities
Troglomorphic	Eyes and pigment absent; antennae long; unguis modified as in neustonic	Caves
Synoecomorphic	Eyes and pigment absent; mouth-parts modified; furcula and legs well developed; unusual scales and setae	Ant and termite nests

been observed (Mayer 1957; Schaller 1953; Betsch-Pinot 1976; Blancquaert 1981). With S. viridis, spermatophores are mainly deposited on leaves and pair forming occurs. Although spermatophores may be deposited in the

absence of a female, only those deposited when the female is present are taken up (Betsch-Pinot 1976). Pair forming with both partners active has also been observed in other Symphypleona including Bourletiella spp. (Lubbock 1868), Sphaeridia pumilis (Blancquaert and Mertens 1977) and Sminthurides spp. (Blancquaert 1981).

Blancquaert et al (1981b) listed the different reproductive strategies that have been observed in Collembola and these involve, (i) the females taking up a spermatophore at the start of each reproductive instar to produce fertile eggs as there is an alternation between reproductive and non-reproductive instars in some groups, (ii) reproduction occurring in each adult instar but the female must be fertilised in each, (iii) reproduction occurring in each adult instar but the females are fertilised only once and (iv) only one adult instar in which the females must be fertilised.

Parthenogenesis has also been recorded for a number of species including Isotoma notabilis and Tullbergia krausbaueri (Petersen 1971) and is particularly well documented in Folsomia candida (Goto 1960; Marshall and Kevan 1962; Green 1964; Snider and Butcher 1973).

(2) Fecundity and oviposition

The eggs of Collembola are laid singly or in batches, the number of eggs and the time required to lay them being highly variable according to environmental conditions (Butcher et al 1971). In laboratory cultures, the number of eggs produced has been shown to be extremely variable. Some females never reproduce and as factors such as pH, temperature and substrates all affect fecundity (Hutson 1978), the different rearing methods make intra-specific comparisons rather difficult (Blancquaert et al 1981b). In reviewing the literature on fecundity in Collembola, Hale (1965a) presented a table of estimates published by a number of workers between 1930 and 1965 (Ripper 1930; Strebel 1932; James 1933; Davidson 1934; Davis and Harris 1936; Lindenmann 1950; Britt 1951; Anders and Anders 1959, Milne 1960; South 1961; Marshall and Kevan 1962; Sharma and Kevan 1963a, 1963b, 1963c). He lists a total of 27 species with estimates of the number of eggs laid in life ranging from 9 in Onychiurus procamptus Gisin to 300 in Entomobrya multifasciata (Tullberg) (Entomobryidae). Other estimates included 84-90 for species of Hypogastrura, 28 for Neanura muscorum (Templeton) (Brachystomellidae), 28-32 for I. notabilis, 91 for I. palustris, 58 for Dicyrtomina fusca (Lucas) (Dicyrtomidae) and 120 for S. viridis. Sharma (1967) stated that Tomocerus vulgaris (Tullberg) oviposited only once in 6 months in laboratory cultures, the number of eggs laid by a female ranging from 6 to 10. Green (1964) recorded an average of 167.5 eggs for Folsomia candida, however Snider and Butcher (1973) showed a surprisingly high fecundity for this species. Oviposition data obtained at 15, 21 and 26°C showed that egg production was highest at 15°C with the mean number of eggs per female being 1344 (max. = 2355); at 21°C the mean produced was

1011 (max. = 1654) and at 26°C 130 (max. = 209).

The egg laying process in Collembola has been described for Isotoma notabilis Sharma and Kevan (1963a), Tomocerus vulgaris (Sharma 1967), Proisotoma minuta (Massoud and Betsch-Pinot 1974) and Onychiurus folsomi (Schaeffer) (Snider 1983). A detailed account of the oviposition process of S. viridis was given by Holdaway (1927), Davies (1928), MacLagan (1932a), and Davidson (1932a). Egg-laying commences in the seventh instar, usually 30-35 days after emergence, providing the temperature is about 13°C, relative humidity is near 100, and soil is available (MacLagan 1932a). Davidson (1932b) considered that the age at which the female begins to lay depends upon the environmental conditions during its development, the shortest periods being 21 days from hatching under laboratory conditions. The observations of Holdaway (1927) and MacLagan (1932a) showed that the female generally laid 2 batches of eggs separated by an interval of about 10 days; the eggs being laid in batches of about 60 eggs/batch in most situations either on the soil surface or beneath decaying leaves and debris (Davidson 1934).

When one or several eggs are placed in position, the female browses on the ground and partakes of soil before another egg is laid. Although the habit of ingesting soil is not restricted to the oviposition period, the female takes in more soil when ovipositing than at any other time. Davidson (1932b) noted that the ventral tube of S. viridis was used on several occasions, being extended and retracted over the soil surface, the walls of the delicate tubes exhibiting active, vibratory movements. He associated this activity with the greater moisture requirements of S. viridis during the process of soil excretion during oviposition.

After laying, the eggs are covered with an anal excretion containing soil and glandular secretions which binds the eggs in a batch, protects them from predaceous mites, other insects and S. viridis (which devours uncovered eggs), prevents too rapid a loss of moisture from the eggs, and assists in distributing moisture over the eggs. Davidson (1934) noted that this egg covering presented a barrier to penetration of less than adequate amounts of moisture for hatching, thus safeguarding the species from hatching by rains inadequate to ensure germination and establishment of food plants. Otherwise, the eggs would hatch after light rains and the immatures would perish either from starvation or dessication if dry conditions prevailed after eclosion.

Protection of eggs by a layer of faecal and substrate material has also been described for other Symphypleona including some Dicyrtomidae (Mayer 1957; Hale 1965a; Butcher et al 1971), Arrhopalites sericus (Massoud and Betsch-Pinot 1973), Bourletiella (Klaver 1975), Heterosminthurus and Deuterosminthurus (Bretfeld 1977 cited by Blancquaert et al 1981a). Eggs uncovered, partly or completely covered have been noted in Sphaeridia pumilis and Sminthurinus aureus (Blancquaert et al 1981a), and uncovered

eggs in Sminthurinus niger (Strebel 1932). Although substrate particles may be attached to eggs of Arthropleona a full covering of faecal and substrate material has not been observed (Mayer 1957).

Factors affecting oviposition

A number of factors including moisture, temperature, soil type and soil pH may affect oviposition in Collembola. Although the individual species studied in most detail is S. viridis, data for other species have accumulated from a number of laboratory studies in recent years including Ashraf (1969), Snider (1973), Snider and Butcher (1973), Hutson 1978, Blancquaert et al (1981a, 1981b) and Snider (1983).

(i) Influence of moisture on oviposition

Davidson (1932b), in his comprehensive study of the soil factors which affect oviposition in S. viridis found that given favourable temperatures, soil moisture was the most important factor. Egg-laying decreased rapidly below about 12% soil moisture (50% saturation) and below about 8% moisture, only a few isolated scattered eggs were laid, there being insufficient moisture for the production of a protective fluid coating. S. viridis will not lay on air-dry soil (2.5% mois.) and under very dry conditions individuals penetrate into cracks in the soil, where the moisture is more favourable; excessively wet conditions are also unfavourable for oviposition and egg batches laid under such conditions are badly formed: eggs are scattered and naked as the wet soil does not allow the soil-excretion to dry and so firm egg batches are not obtained. The amount of moisture in the soil at the beginning of the rainless period is important, the less moisture present the sooner will the moisture content fall below the value favourable for oviposition. The water-holding capacity of the soil is important in this regard.

MacLagan (1932a) stated that almost 100% relative humidity was necessary for maximum oviposition but his findings were refuted by Walters (1964) who observed that maximum oviposition occurred at 90% saturation with an optimum moisture range of 75-90% saturation. MacLagan (1932b) considered that the intrinsic requirements of the oviposition process in S. viridis included a very high rainfall during the progress of oviposition, this requirement probably being associated with the coating of each egg with the soil-excreta fluid, the passage of which through the alimentary tract required that the soil be in a very moist condition. MacLagan's experiments confirmed the suggestion of Holdaway (1927) that the presence of soil had a stimulatory effect on oviposition. Further, Davidson (1934) demonstrated that if S. viridis females which were ready to lay were denied access to soil, oviposition was delayed.

(ii) Influence of temperature on oviposition

When moisture conditions are favourable, temperature may be the most important factor limiting oviposition, the optimum temperature varying according to species.

Davidson (1934) found a marked reduction in number of eggs laid by S. viridis when the temperature at the soil surface was raised from 15°C to 25°C; no eggs were laid at 30°C. Walters (1964) observed oviposition in field collected female S. viridis (that may have already oviposited) at 26.7, 21.1, 15.6, 14.8 and 12.2°C. He found that maximum oviposition occurred at 15.6°C (22.6 eggs per female) with oviposition decreasing as temperatures increased or decreased from this temperature.

Blancquaert et al (1981b) studied the effect of temperature variation on the Symphypleone species Sminthurides aquaticus, Sphaeridia pumilis and Arrhopalites sericus. For S. aquaticus, 14.4 eggs per female were laid at 15°C and very few at 30, 25 and 10°C. For S. pumilis, the number of eggs decreased with decreasing temperature ranging from 11.4 eggs per female at 30°C to 2-5 eggs per female at 5°C. For A. sericus, oviposition was observed at 10, 15, 20, 25 and 30°C, the optimum of these being 15°C with 17.4 eggs per female recorded.

Sharma and Kevan (1963a) found that lowering the temperature from 17°C reduced the total number of eggs laid and the number of ovipositions for I. notabilis, with no eggs being produced at 0°C. Snider and Butcher (1973) reported that the mean number of eggs produced by F. candida progressively decreased as the temperature was increased over a range from 15 to 26°C.

(iii) Influence of soil type on oviposition

S. viridis may deposit eggs on a soil surface which may be physically unfavourable as, in temperate climates, the soil surface is subject to diurnal fluctuations. If the eggs were deposited on either the herbage or below the soil, they would be subject to less violent fluctuations. The physical character of the soil affects the period over which oviposition takes place and also affects the number of eggs deposited. S. viridis exhibits a selective action in its choice of soil on which to oviposit, a phenomenon in which MacLagan (1932a) considered the sense of taste to play a primary role.

The water-holding capacity of the soil is of utmost importance because of its direct influence on soil moisture and thus coarse, sandy soils are unfavourable for oviposition due to their low water-holding capacity and large particle size (Davidson 1934). S. viridis shows a definite preference for clay soils over sandy soils as sites for oviposition (Davidson 1932b). However, Walters (1964) considered that there was no real difference in the number of eggs laid on clay and sand except that the naked eggs on the sand were devoured by S. viridis, thus giving a lower apparent oviposition response on the latter soil type. MacLagan (1932a) suggested that the effect of soil type on oviposition was exerted through its effect on nutrition on the adult as soil is an important part of the diet, particularly during the reproductive phase. Holdaway (1927) showed that in the absence of soil, the average number of eggs laid was

28 per female whereas with suitable soil provided, the average was 118 per female.

(iv) Influence of pH on oviposition

It has been shown by Holdaway (1927), Davidson (1932b) and MacLagan (1932a) that pH has a marked effect on the number of S. viridis eggs laid, as well as influencing the development and vigour of the species. Females oviposit over a pH range of 5.5 to 7.0 (Davidson 1934), maximum oviposition occurring at pH 6.5 (MacLagan 1932a) although Johnston (1960) listed the pH range as being from pH 5.5 to 8.0. However, S. viridis occurs on certain reclaimed swamp soils near Murray Bridge (South Australia) with a pH of 5.4 and thus S. viridis can flourish on tolerably acid soils. As the soil becomes more alkaline there is a decrease in the number of egg batches (Davidson 1932b).

Walters (1964) found no significant difference with soils of pH 4.1 and pH 7.8 as regards oviposition sites for S. viridis. The greatest number of eggs was laid on soil with pH 6.3 and departure from this optimum to the acid side had a greater detrimental effect on fecundity than a similar departure to the alkaline side (MacLagan 1932a; Walters 1964).

Studies show that variations in pH may also have a profound effect on oviposition in other Collembola. Ashraf (1969) found the number of eggs laid by groups of 15 adults of Onychiurus bhattii Yosii after 14 days ranged from 295 at pH 7.2 to nil at pH 9.7. Hutson (1978) examined fecundity in 4 species of Collembola at pH values ranging from 2.5 to 7.6 and found the optimum range was between 4.3 and 6.2, with maximum oviposition occurring at 5.2 for F. candida, Tullbergia krausbaueri and I. notabilis and 7.2 for P. minuta.

(v) Influence of population density on oviposition

The number of eggs laid per individual S. viridis decreases approximately in the form of an arithmetical progression with an increase in population density in the form of a geometric progression (MacLagan 1932a; Wallace 1957). MacLagan (1932a) suggested that the observed density-dependent variation in number of eggs laid per individual might be non-specific and this was confirmed by Walters (1964) who demonstrated a depression in egg production per individual S. viridis with increases in density of S. viridis or other insects or mites in the environment. The reduction is probably due to increasing mechanical disturbance of ovipositing females associated with increases in population density. Such disturbance would interfere with the coating of eggs with soil-excreta fluid and ovaphagy would be likely to occur with high numbers of naked eggs present. S. viridis is very sensitive to contact influences and individuals distribute themselves to avoid neighbouring contact (MacLagan 1932a). Green (1964) found that a reduction in the fecundity of F. candida (var. distincta (Bagnall)) occurred in culture as conditions became more crowded. Crowding during periods other than when oviposition occurred

did not cause a reduction in fecundity. He suggested that the reduced fecundity was a manifestation of stress caused by jostling.

Studies by Snider (1973) showed that egg production in low density cultures of Onychiurus folsomi was four times that in mass cultures.

(vi) Influence of host plant on oviposition
The host plant was found by Walters (1964) (in South Africa) to exert a marked differential influence on the fecundity of S. viridis with the egg production from individuals feeding on capeweed and lucerne being 5-6 times that on maize. Thus, using one kind of food for any given species during estimates of fecundity in laboratory cultures may introduce serious errors and mask the fecundity that occurs under natural conditions (Butcher et al 1971).

(vii) Influence of age on oviposition
Studies on F. candida by Snider (1973) showed that the number of ovipositions achieved by an individual ranged from 3-20 depending on life span, progressive age causing an increase in the number of days elapsing between ovipositions and a decrease in egg viability.

(3) Egg Development
When first laid collembolan eggs are spherical and smooth, white or coloured and start to increase in size due to the uptake of water (Butcher et al, 1971). Hale (1965a) presented data on the morphological changes that take place during egg development of species from the families Hypogastruridae, Brachystomellidae, Onychuridae, Isotomidae, Entomobryidae, Tomoceridae and Dicyrtomidae and Davidson (1934) described embryonic development in S. viridis.

Factors affecting egg development
Davidson (1934) showed that the duration of development of S. viridis eggs is dependent on humidity and temperature.

(i) Effect of moisture on development and viability of eggs
When temperature is favourable, moisture is the dominating factor influencing development of S. viridis (Davidson 1934), a factor which was emphasized by Holdaway (1927), moisture becoming increasingly important with temperatures below 10°C and above 20°C owing to the tendency to wetness and dryness, respectively. Egg development is retarded when soil moisture is maintained below 10% and hatching does not take place with less than 5% soil moisture. Davidson (1934) regarded 60-80% saturation of surface soil as optimal for S. viridis. Walters' (1964) observations confirmed this optimum range; MacLagan (1932a) stated that an environment of 100% relative humidity and 16°C was highly favourable for egg development. The water requirements of the final stages of egg development are greater than those of the earlier stages so that contact with free moisture is necessary for the completion of development and

eclosion (Davidson 1933c; Walters 1964).

(a) Insufficient moisture

When free moisture is not available from the soil, the soil-excreta surrounding the eggs of S. viridis will dry out and if atmospheric moisture is insufficient for the requirements of the eggs, development will be retarded or inhibited according to the degree of dryness.

Davidson (1932a) found that the viability of eggs under the adverse effects of dryness depended on the degree of development attained before extreme dryness set in, viability being greatest where embryos have undergone 50% development. The enhanced resistance of half-developed eggs to unfavourable conditions appears to be due to the production at that stage of an almost impermeable embryonic membrane, the blastodermic cuticle, beneath the egg-shell. Eggs which have made only slight development and those which are approaching the final stages of development are less able to withstand subsequent dry conditions. Other factors affecting the viability of eggs in a drought period include the character of the soil and vegetative covering, meteorological factors influencing evaporation, and the duration of the dry period. When the soil is drying out, some eggs continue development for a time after moisture values have fallen below 5% (40% saturation) in the surface soil, partly due to moisture available for particular eggs in localised situations and also to moisture retained as "bound water" within the egg (Davidson 1932a). This results in a "banking up" of eggs at a relatively advanced stage of development and, when the soil becomes moist again, general hatching takes place after a relatively short period. This enables the species to take full advantage of temporary periods of favourable moisture conditions.

(b) Excess moisture

Excess moisture is harmful to developing eggs of S. viridis as they may become distended, the chorion caps separating prematurely and the embryo disintegrating (Davidson 1934). If moisture conditions on the soil surface are too wet, egg development may be retarded or inhibiting (MacLagan 1932a) and there is a greater possibility of fungal and other diseases. With undisturbed egg batches, S. viridis mortality may be heavy if the soil-excreta surrounding the eggs is permanently saturated as this results in a shortage of oxygen available for the developing embryos. However, certain partially developed eggs may withstand complete immersion in water for long periods and even undergo a certain amount of development under such conditions (Davidson 1933c). This apparent resistance of certain S. viridis eggs to immersion may be due to the presence of air-cavities in the soil-excreta coating.

(ii) Effect of temperature on egg development

Davidson (1934) showed that when moisture surrounding S. viridis eggs was optimal, time for development (D) in relation to temperature (T) could be

expressed as a hyperbola:

$D(T-C) = K$ where $C = 5.5°C$ (developmental zero or critical cold point)
$K = 161°C$ (thermal constant)

The reciprocal values of this expression lie on a straight line, the velocity curve, which cuts the x-axis at the "critical cold point" or "threshold of development" below which temperature development ceases.

At 11°C development takes approximately 28 days; at 15°C approximately 15 days. A minimum incubation period of 8 days was obtained at 25°C; no eggs hatched at 30°C or 34°C (Davidson 1933d). MacLagan (1932a) and Walters (1964) demonstrated a similar reduction in incubation period as temperatures increased to 27°C; eggs perished with temperatures above 32°C. MacLagan (1932b) gave 9-21°C as limits for egg development with a developmental zero of 7.2°C, although partially developed eggs were able to retain their viability when maintained at temperatures below the developmental zero. Low temperatures extended the incubation period considerably and no eggs hatched at 6.3°C (Davidson 1931). Walters gave the developmental zero for S. viridis as 5°C.

Hale (1965a) used fourteen species of Collembola in experiments on egg development periods. He also found a linear relationship between temperature and the reciprocal of the development time, with development zeros occurring in a range between 0°C and 3°C. Blancquaert et al (1981a) used the formula of Davidson (1934) and calculated developmental zeros for Sminthurinus aquaticus, Arrhopalitus sericus and Sphaeridia pumilis at 12.7, 7.2 and 7.8° C respectively. They considered that these were rather high in comparison to S. viridis (5.5°C) and species observed by Hale (1965a), on the basis that the real value of the developmental zero was known to lie below the computed value (Wigglesworth 1953). Walters (1964) studied the influence of temperature on the viability of S. viridis eggs and found optimal survival at 15°C similar to that reported by Blancquaert et al (1981a) for Arrhopalitus sericus. Snider (1973) showed a close relationship between temperature and egg stage duration in Onychiuria folsomi, the optimum range for development occurring between 15.5° and 21.1°C.

(4) Egg Hatching

Comprehensive descriptions of the hatching of eggs of S. viridis were given by Holdaway (1927), Davidson (1932a) and Walters (1964). High temperatures after a heavy summer rain cause rapid drying of the egg covering before moisture can penetrate and initiate hatching. With lower temperatures and slower drying, a substantial autumn rain results in a high hatching rate and most eggs hatch over a short period of time.

Davidson (1934) defined the time of hatching of oversummering eggs of S. viridis as being during the months in which the rainfall (R)/evaporation

(E) ratio rises above a value of approximately 1.0. Similarly, numbers will decline at the end of the wet season in the month in which the value of the R/E ratio falls below a similar value.

Factors affecting hatching

Hatching is affected primarily by soil moisture and temperature.

(i) Influence of moisture on hatching of S. viridis eggs

Hatching of eggs in the field will only take place when adequate moisture at the soil surface is maintained for long enough to allow completion of the last stage of development (Walters 1964). Swan (1940) stated that "over-summering eggs of S. viridis do not hatch until the soil surface becomes permanently moist for about a week". The degree of moisture necessary for general hatching is higher than that required for development of the egg to continue. The actual moisture content of the soil and soil-excreta coating the eggs is important, not the atmospheric humidity.

Experiments by Holdaway (1927) indicated that under constant moisture conditions the duration of the egg stage was 8-10 days. With favourable temperatures, the character of the hatching curve (Davidson 1933c) reflects the influence of moisture conditions.

Low soil moisture extends the incubation period and, with soil moisture values below 7%, reduces the number of eggs which hatch. The value below which hatching ceases depends on the soil type (Davidson 1932a). Above 80% saturation, conditions are too wet, resulting in the retardation of certain eggs and a reduction in the number of eggs which hatch.

(ii) Influence of temperature on hatching of S. viridis eggs

With optimum moisture conditions, eggs commence hatching after 67 days at 7°C (Walters 1964); 12 days at 15°C (Davidson 1934); and after 8 days at 27°C (Walters 1964). Davidson (1934) found that a temperature range of 9-25°C was most favourable for hatching and development of immatures, the effect of soil moisture content on survival of young nymphs becoming increasingly important with departures from this range, owing to the tendency to drowning at lower temperatures when wet, and to desiccation at higher temperatures when dry. However, MacLagan (1932b) considered that temperatures above 14°C reduced numbers of emerging nymphs and at 19°C there was little emergence. He predicted the presence of nymphs in the field in spring whenever the mean maximum temperature reached 15°C. Davidson (1934) obtained hatches of 94% and 92% at 25°C and 20°C, respectively, under optimum moisture conditions.

Delayed Hatching

The hatching of all S. viridis eggs within a batch may extend over 36 days (Walters 1964) and this has been attributed to (a) effects of variation in size and compactness of the egg batches on the protection

afforded to particular eggs with respect to surrounding temperature and moisture, (b) to individual peculiarities of particular eggs (thickness and permeability of chorion), and (c) to slight differences in age (Davidson 1932a). Walters (1964), however, showed that delayed hatching is not due to differences in temperature and moisture relations of individual eggs (as the phenemenon occurred even in batches where the eggs were incubated in isolation from each other on moist filter paper under identical conditions), but to intrinsic differences between individual eggs. This irregularity of hatching, which is more pronounced in batches that have been subjected to a temporary drought period, constitutes a mechanism ensuring survival of S. viridis.

5. Post-embryonic development

The number of moults and time required to reach sexual maturity varies considerably between collembolan species (Butcher et al 1971). Christiansen (1964) in his review of the literature found the number of moults before sexual maturity was reached and ranged from 3-12 although a considerable majority required from 4-6 moults.

James (1933) recorded 7 instars before oviposition in I. palustris and 4-5 were noted by Sharma and Kevan (1963a) for I. notabilis. Hale (1965b) recorded the number of instars up to maximum size for Hypogastrura denticulata (Bagnall) (6), Tullbergia krausbaueri (Boerner) (4), Onychiurus procamptus Gisin (6), O. latus Gisin (7) O. tricamptus Gisin (6) and O. furcifer (Boerner) (7). He found that eggs were not usually laid until maximum size was reached although H. denticulata and T. krausbaueri laid some eggs in the fifth and third instars respectively.

In the Arthropleona moulting continues after the adult stage has been reached and, although little size increase occurs in the later instars, it may continue throughout the entire life span. This has been shown for many species (Britt 1951; Sharma and Kevan (1963a) including F. candida in which a maximum of 45 moults have been recorded (with a mean of 30) in laboratory cultures at 21°C (Snider 1973) and Hypogastrura viatica in which 67 moults were recorded in males and 69 in females (Mertens et al 1983).

Evidence to date suggests that the number of instars in the Symphypleona is more limited. Ashraf (1969) recorded 5 instars in Sminthurinus mime Boerner before it reached sexual maturity and only one further moult was recorded. Studies by Blancquaert et al (1981b) showed that males of Sphaeridia pumilis and Sminthurinus aquaticus moulted 3 times, females of S. pumilis moulted only twice and a maximum of 10 instars was counted for females of S. aquaticus. In S. pumilis, males and females did not moult in the adult stage.

MacLagan (1932a) determined 7 moults (i.e. 8 instars) for S. viridis and plotted growth curves showing the point of attainment of various instars

and the amount of food eaten throughout the growth period. He was the first to apply Dyars' Law to the Collembola in order to distinguish various instars. Walters (1964) differed with MacLagan showing that S. viridis females underwent 9 moults, passing through 10 instars and that males attained maturity in the fifth instar and females in the sixth instar. Dentener (1985) found it possible to determine the sex of individuals at an earlier stage and also recognised 5 instars in S. viridis males. He only noted 6 instars in females, grouped together Walters' third and fourth larval instars, and did not observe the last three instars described by Walters.

Factors affecting post-embryonic development

The time required for collembolan immatures to develop through to sexual maturity depends on a number of factors.

(i) Influence of temperature on post-embryonic development

Temperature is one of the most important factors affecting post-embryonic development in Collembola. Data on rates of development over the life span of individuals at different temperatures for species other than S. viridis is scarce, although some data for Arthropleona species is reported including Milne (1960) (Tullbergia krausbaueri, Onychiurus spp., F. candida, Isotoma viridis, Neanura muscorum); Sharma and Kevan (1963a) (Isotoma notabilis) and Snider (1973) (F. candida). Other authors are reviewed by Christiansen (1964).

For S. viridis, MacLagan (1932a) found that the period from hatching to oviposition occupied 28 days at 16.7°C and 38 days at 13.0°C with a developmental zero of 2.7°C. Similarly, Davidson (1933d) demonstrated the development of nymphs from eclosion to adults in about 50 days with mean monthly temperatures of about 10°C and in about 30 days at 15°C. Thus, increases in temperature are associated with an increasing rate of nymphal development up to 25°C, although temporary exposure to temperatures as high as 35°C had no effect on mortality (Walters 1964). This upper limit is higher than that set by MacLagan (1932a) who found that the growth rate of immatures increased from 3°C up to a limit of approximately 17°C and decreased rapidly between 17°C and 21°C with nil survivors at 21°C (MacLagan 1932b).

(ii) Influence of moisture on post-embryonic development

The death rate of S. viridis immatures increases with increasing saturation deficit, which is the major influence determining survival of the post-embryonic stages (Davidson 1934). Under very humid conditions, the species becomes distended and in extreme conditions mortality may be high, particularly at temperatures above 20°C and during the first four instars. MacLagan (1932a) found 100% relative humidity optimal for development but saturated air conditions were regarded as unfavourable by Davidson (1934) and Walters (1964).

(iii) Influence of soil on post-embryonic development
During the first 12 hours of its life, the first instar of S. viridis is attracted more strongly to soil than to food, indicating that for the normal physiology of S. viridis during its early life, soil is a greater necessity than plant material. The absence of soil results in less growth, but does not seem to affect the duration of life (Holdaway 1927).

(iv) Influence of pH on post-embryonic development
Christiansen (1964), in his review, cited several authors who had found no correlation between soil pH and population numbers. However, Bååth et al (1980) reported that acidification caused an increase in numbers of Tullbergia krausbaueri and more recent work by Hågvar (1984) indicates that changes in soil pH can affect the abundance of a large number of collembolan species. He showed that pH significantly influenced the colonisation process of 7 collembolan species. For instance, he classed Tullbergia krausbaueri as acidophilic and Isotoma notabilis as calciophilic. However, species such as Onychiurus armatus and Isotomiella minor Schaeffer appeared highly tolerant to changes in soil pH although in certain soils O. armatus populations were reduced by liming and those of I. minor had higher abundance in limed compared to acidified samples, suggesting that in some soils, pH may be important for these species within certain parts of the scale (Hågvar and Abrahamsen 1980). In general, a pH range of 6.0-7.8 appears to be well within the tolerance of most species (Davis 1963). For S. viridis a soil pH of 6.5 was most favourable for development of immatures (Holdaway 1927; MacLagan 1932a), although there were no real differences in the rate of development for immatures reared at pH levels ranging from 6.3 to 12.1. At pH values below 6.3 development was retarded and no S. viridis attained sexual maturity (Walters 1964). Development was very much retarded at pH 4.1, the retarding effect being chiefly restricted to the acid side of the pH scale (MacLagan 1932a).

Maclagan (1932a) considered that the time required for attainment of sexual maturity was a linear function of the deviation from optimum pH, although the mechanism of this process in still unclear.

(v) Influence of food quality on post-embryonic development.
There is little information available on the influence of food quality on development in Collembola. Walters (1964) considered that the poliphagy of S. viridis suggested that different food plants might cause differential rates of post-embryonic development of this species. However, rearing both males and females on a range of food plants (capeweed, Arctotheca calendula; wild clover, Medicago denticulata; wheat, Triticum aestivum; lupins, Lupin albus) showed that there were no significant differences in growth rates. Booth and Anderson (1979) found that fungal food quality affected growth rate in Folsomia candida. They also showed that the growth (and fecundity) of this species could be indirectly stimulated by increasing the nitrogen supply to the fungus.

6. Longevity and survival

Many estimates of the longevity of collembolan species may be unreliable as they are mainly based on laboratory studies, however, it seems that in temperate regions most species probably live from four to five months although many can live for shorter time periods of 2 months or for longer periods of more than a year (Christiansen 1964; Hale 1967). However, Aitchison (1984) reports that species from areas with lengthy periods of sub-zero temperatures (high altitudes, arctic or sub-arctic climates) may have prolonged life histories ranging from one to seven years. Arthropleona live much longer then Symphypleona at the same temperatures which may relate to the higher number of adult instars in the former group (Blancquaert et al 1981b). Mertens et al (1983) concluded from studies on post-embryonic development in H. viatica at 20°C that under the conditions imposed, its lifespan was approximately 1 year with ca 50% of the animals dying before the age of 174 days. Longevity estimates for Folsomia candida have been made by Marshall and Kevan (1962) who recorded a life span of 111 days (with a maximum of 12 moults) at 24°C; by Green (1964) who recorded 230 days (maximum number of moults > 25) at 25°C, and by Snider (1973) who recorded an average longevity of 136 days (maximum number of moults 45) at 21°C, the oldest specimen dying after 198 days.

Davidson (1934) noted that S. viridis lived for a maximum of 83 days after hatching in insectary rearing cages, the mean life span being 64 days. Studies by Walters (1964) on S. viridis reared in the laboratory at 20°C showed that the average life span of males at this temperature was 46.8 days and that of females 44.9 days, showing no intrinsic difference in longevity bewteen the sexes. Longevity in Collembola is obviously dependent on environmental factors and probably species specific, being its greatest at lower temperatures and decreasing with increased temperature. Moisture relations are also important, dry conditions leading to an increased motality (Snider and Butcher 1973).

(i) Influence of temperature on longevity and survival.

Studies by Snider and Butcher (1973) on Folsomia candida showed that a temperature of 26°C shortened its life span to a mean of 72 days compared to 136 days at 21°C. At 15°C longevity was extended to 240 days. Mortality reached 100% after 115 days at 26°C, 198 days at 21°C and 352 days at 15°C.

Walters (1964) showed that longevity in S. viridis decreased with an increase in temperature, his results being summarised in the following Table.

Table 1.3 Effect of temperature on longevity in S. viridis (after Walters 1964).

Temperature °C	Mean longevity (days) ♂	♀
14.4	61.5	65.5
16	52.7	64.8
20	45.3	43.7
25	26.5	30.4

He also showed (Fig 1.1) that an increase in temperature stimulated development of immatures at least up to 25°C and stated that S. viridis should be able to survive at temperatures up to 25°C in the field, but only under irrigated conditions. Maclagan (1932a) found that temperature increases from 13-17°C and from 17-21°C each reduced longevity by 34% and that temperatures below 13°C caused a slight increase in the total life span, provided the temperature did not fall below 3°C, the optimum temperature for survival being 8°C.

At temperatures below freezing, S. viridis dies off rapidly due to the gradual drying out of the atmosphere and the adverse effect of low temperatures. The species still moves about and feeds at 0°C, as long as the atmosphere remains very humid (MacLagan 1932b). However, there is also a "critical cold point" of 5.5°C, the temperature below which the eggs of S. viridis will remain dormant (Walters 1964). Walters also showed that first instars were far more susceptible to high temperatures and starvation than later instars, and could only survive for 60 hours at 26.6°C in comparison with 104 hours for third to fifth instars at the same temperature.

(ii) Influence of humidity on longevity and survival

As a group, the Collembola have a general dependence on high humidities, but the requirements of individual species may vary considerably according to their habitat preferences, as was demonstrated for species of Entomobrya by South (1961). Davies (1929) examined the effect of variations in relative humidity (RH) on the longevity of 5 species of Collembola (including S. viridis) and found that although all species were susceptible to dry conditions, S. viridis and Entomobrya multifasciata (Tullberg) were much less susceptible than the other species tested. S. viridis showed 100% mortality within 15 hours in an atmosphere of 20% RH and within 30 hours at 50% RH. The most susceptible species, Isotoma viridis Bourlet showed 100% mortality within 30 minutes at 20% RH and within 1 hour at 50% RH.

The lower susceptibility of S. viridis to dryness is due the presence of a tracheal system which is also possessed by some other species of

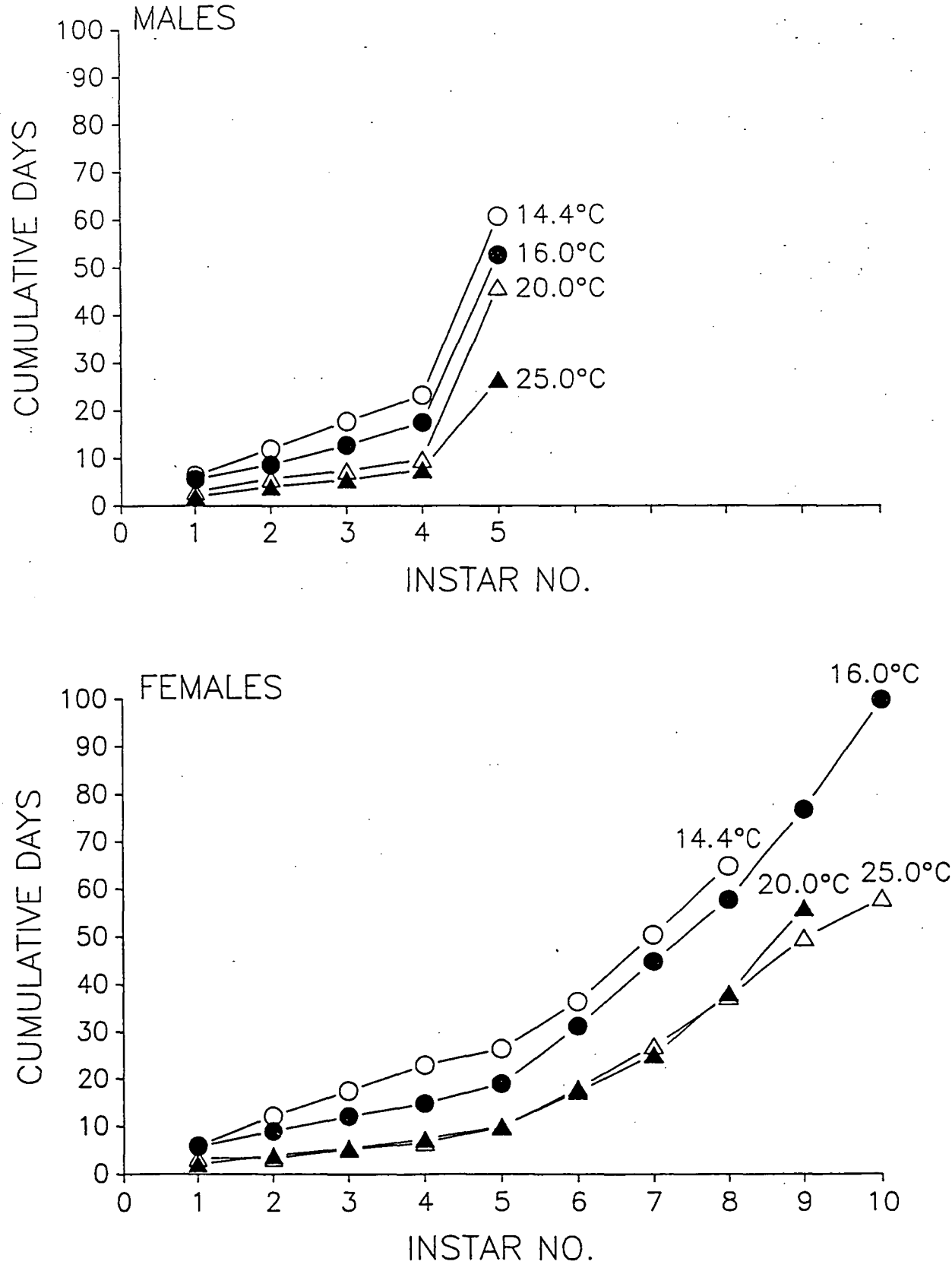


Fig 1.1 Effect of temperature on the development of S. viridis (after Walters 1964)

Symphypleona (including Bourletiella spp.) (Davies 1927, 1929), although not present in Entomobrya (it appears some other physiological mechanism may be involved in the high tolerance of some Entomobrya species to low humidities). In most Collembola, respiration takes place through the cuticle, however, the presence of a tracheal system results in independence of gaseous exchange across the cuticle, reducing evaporation, thereby making the species less susceptible to moisture stress (Davies 1929). Temporary periods of low humidity in the field would therefore not be expected to exert a great influence on the mortality of active stages of S. viridis.

MacLagan (1932a) considered that 100% RH was optimum for survival of S. viridis and the higher the humidity, the greater its resistance to the adverse effects of high temperature. Walters (1964) found that saturated air conditions were most favourable for survival only when sources of moisture such as green food were not available.

SURVIVAL MECHANISMS

Because the survival of Collembola is greatly affected by humidity, they may live in a constantly damp environment which may exist in deep soil or may live in a changing environment at the soil surface. Some of these are extreme and range from arctic and alpine regions to deserts (Joosse 1983). To live in these situations species have evolved a number of mechanisms to enable their survival.

(1) Diapause

Responses to adverse humidity and temperature conditions often consist of temporary states of inactivity referred to as quiescence (Testerink 1983). When environmental changes induce this state of inactivity in advance of the adverse condition, it is called diapause (Beck 1980). Such a state of inactivity persists even when environmental conditions are favourable for growth (Harvey 1962).

Some collembolan species (eg. S. viridis) survive hot, dry summers as diapausing desiccation resistant eggs (Wallace 1968), this inactive stage being reversed by the onset of favourable conditions. The resting conditions of the over-summering egg is not a definite rhythmical diapause, but an enforced condition imposed by the absence of moisture necessary for development (Davidson 1932a; MacLagan 1932a).

Davidson (1934) showed that egg development in S. viridis was retarded by departures from the optimum moisture content and, when extreme, was arrested temporarily or permanently. When eggs were dried out between the 1st and 5th day after commencing to develop they passed into diapause in which state they remained viable for over 12 months (if kept dry at ordinary temperature) and hatched in 3-7 days at 22°C when thoroughly moistened. From laboratory experiments and field observations, Wallace (1968) concluded that an 'aestivating diapause' occurred in the egg

batches of S. viridis, such eggs being first produced in early spring or late winter.

(i) Diapause induction

S. viridis produces aestivating eggs in response to maturing herbage of annual plants. The experiments of Wallace (1968) indicated that the effect of changed food (i.e. transfer to either young or older foliage) was first evident (from the proportions of diapause and non-diapause eggs laid) about 20 days after transfer e.g., transferring S. viridis to a less mature pasture induced them to lay mostly non-diapause eggs.

The aestivating eggs must be exposed under natural conditions in the field at least until mid-December before they can accomplish diapause development and later resume morphogenesis. This is a beneficial adaptation for the population since S. viridis hatching late in spring would be unlikely to find enough green plant material to ensure survival. In northern Europe, S. viridis overwinters in the egg stage (MacLagan 1932a) and the food plants grow principally in the summer and mature in the autumn. It is therefore possible that the eggs S. viridis produces to survive the cold European winters (MacLagan 1932b) are diapause eggs (Wallace 1968).

(ii) Diapause development

Breaking up of egg batches or washing the soil-excreta coating the eggs, releases the inhibitory effect of diapause. Alternatively, dry storage for 2 or more weeks at about 30°C or lower is partially effective in enabling diapause eggs to develop rapidly when remoistened (Wallace 1968). Wallace suggested that in the Mediterranean-type summer, moistening by occasional falls of rain followed by desiccation, gradually breaks up the egg batches, promoting rapid development in the autumn with the onset of autumn rains. In northern Europe, periodic freezing and thawing could have the same effect.

Apart from S. viridis, there are few records of diapause in the Collembola. The life cycle of Anurida maritima (Guerin) in Europe suggests it occurs in this species, which lays eggs in November that do not hatch until April (Joosse 1966). It may also occur in Dicyrtomina spp. which produce two kinds of eggs, summer and overwintering, the latter of which require longer incubation periods (Hale 1965a). Blancquaert et al (1981a) proved the existence of diapause eggs in Sminthurides aquaticus, Sphaeridia pumilis and Sminthurinus aureus and more recently it was shown to occur in the entomobryid Lepidocyrtus lignorum Fabricius, the eggs of which have a diapause terminated by cold, the species overwintering as juveniles and adults (Leinaas and Bleken 1983). Wallace (1971) showed that the eggs of an important predator of S. viridis, the bdellid mite Bdellodes lapidaria (Kramer) also underwent an aestivating diapause in southern Australia, the egg hatching being synchronised with S. viridis in autumn which ensures a plentiful food

supply for the predator.

(2) Other survival mechanisms

The effects of low humidity on Collembola were reviewed by Butcher et al (1971) and apart from higher mortality have been found to result in alterations in behaviour patterns, migration, lower reproduction, construction of protective cells, retardation of sexual development, and patterns of inactivity.

Adaptations to aridity were discussed by Greenslade (1981) and a comprehensive review on survival mechanisms in arctic and alpine regions, dry, intertidal and polluted environments is given by Joosse (1983).

In temperate regions, some species empty their guts in response to dry conditions in summer and cold conditions in winter (Testerink 1983). In summer drought periods, the process results in a reduced transpiration rate (Vannier and Verhoef 1978; Testerink 1981) and in cold periods during winter a lowered supercooling point to prevent ice crystals forming in body fluids (Block and Zettel 1980; Testerink 1981). Supercooling as a survival mechanism for the sub-antarctic species Cryptopygus antarcticus Willem has been noted by Søme (1978) who records this species as supercooling its body fluids to -27°C.

Although many Collembola seem to aestivate in the egg stage some may survive dry summers in the adult stage. Adaptations such as the presence of scales and dense cover of hairs may reduce water loss in some species (e.g. some Entomobrya spp.). Others may undergo anhydrobiosis, a process in which species become inactive desiccation resistant, dehydrated individuals which rapidly become reactivated following re-hydration after heavy rain. This has been recorded for some species by Poinsot (1968, 1974). Ecomorphosis is another process by which some species of hypogastrurids and isotomids may respond to dry conditions by undergoing morphological changes in the cuticle together with internal changes (Cassagnau 1971). However, there now is evidence to show that the onset of ecomorphosis is genetically fixed in a species and not simply a response to unfavourable conditions (Fjellberg 1985).

Massoud et al (1968) records some species of Onychiurus as constructing protective chambers of faecal pellets in response to dry conditions. Drought has also been found to stimulate locomotory activity in some species, leading them to aggregate in conditions of optimal humidity, thereby increasing their survival rate (Joosse and Groen 1970).

SWARMING

Swarms or large aggregations of Collembola have frequently been reported in the literature (Brown 1921; Davies 1932; Turk 1932; Wray 1945; Park 1949; Paclt 1956; Goto 1957; Poole 1961; Hale 1966). According to Christiansen (1964) the most common species involved is the European Hypogastrura socialis (Uzel) which commonly swarms on snow (Paclt 1956;

Leinaas 1981). Other Hypogastrura species recorded have been H. purpurescens (Lubbock) (Brown 1921), H. viatica (Tullberg) (Brown 1921; Turk 1932) H. armata (Nicolet) (as Achorutes armatus Nicolet) by Wray (1945) and H. bengtssoni Agren by Park (1949). Further records are listed in the reviews by Paclt (1956) and Christiansen (1964). More recently Mari Mutt (1978) recorded Entomobrya unostrigata Stach as swarming over footpaths, parking lots and lawns and Greenslade and Fletcher (1986) record Proisotoma filifera Denis as forming dense aggregations on the substrate material in earthworm rearing beds. Although the terms 'swarming' and 'aggregation' seem to be used interchangeably in the literature to refer to large congregations of Collembola, 'swarming' can be distinguished from other forms of aggregation when consisting of up to several hundred million individuals (Paclt 1956) lacking a habitat component and usually involved in unidirectional movement (Goto 1957). Other types of aggregation involve a smaller number of relatively immobile individuals which come together as a result of undirected movements (Joosse 1970). Hale (1966) explained the formation of aggregations as the result of the slow dispersion of individuals from an egg batch after hatching which gather at one point probably at a food source or in a microhabitat in which optimum conditions prevail. Joosse (1970) makes a distinction between active and passive aggregation, depending on whether movements are directed (active aggregation) or undirected (passive aggregation) by an environment component.

The biological significance of aggregation was discussed by Joosse (1970,1971), Verhoef and Nagalkerke (1977), Usher et al (1979) and Leinaas (1983) and involves synchronisation of moulting, reproduction and protection against adverse environmental conditions. The occurrence of aggregation pheremones which trigger gregariousness in Collembola was demonstrated by Joosse and Koelman (1979) and Leonard and Bradbury (1984). Aggregations only exist in optimum conditions when moulting takes place, during which Collembola are very sensitive to desiccation (Joosse 1970). As a result, the process must take place in optimum humidities otherwise activity is stimulated and animals aggregate where optimum conditions are available, mortality occurring if unsuitable conditions cannot be located (Joosse op. cit.). Leinaas (1983) found that moulting was independent of age and synchronised within aggregations by chemical communications, suggesting that co-ordinated migration in a swarm may be possible only if the moulting cycle is synchronised. Aggregation increases the chance meeting of male and female and is therefore important in reproduction, which occurs in Collembola shortly after ecdysis in alternating moulting instars (Joosse 1970).

SEASONAL OCCURRENCE

Studies on the Collembola of grasslands (mainly euedaphic and hemiedaphic species) have shown that the pattern of population fluctuations varies not only from species to species but also from year to year (Glasgow

1939; Milne 1962). Peaks in population numbers may occur in any month although late summer is generally unfavourable (Christiansen 1964). For instance, Sharma and Kevan (1963a) showed that populations of Isotoma notabilis in eastern Canada were highest in June, however, there was a decline of numbers in July which continued into August. The usual cause of a summer minimum is the dry conditions which may be experienced at this time of year, however, late summer maxima were recorded for several spcies (including I. notabilis and Tullbergia krausbaueri) in core samples by Poole (1961) over a 12 month period, in conditions where moisture was not a limiting factor. Sphaeridia species commonly occur in habitats subject to abrupt changes which can result in closely synchronised development of a species population (Murphy 1966) and may become active at any time of the year if conditions are suitable. Sphaeridia have dessication resistant eggs and a short life history (Blancquaert et al 1981b) and only a week is needed for the full cycle of development (from egg to adult to egg) provided moist conditions prevail (Greenslade 1981). Phenological variations between species have been attributed to differences in optimal climatic requirements and the length of post-embryonic development (Milne 1962). Christiansen (1964) reviewed a number of studies which primarily involved sampling hemiedaphic and euedaphic species. Grouped population data from the sampling showed that population peaks for Collembola occurred in spring and autumn in central Europe and parts of the United States, and occurred in summer and winter in England and other regions of North America. In New Zealand, independent studies by McMillan (1969) and Adams (1971) showed that total collembolan populations extracted from grassland soil attained their maximum levels in autumn and winter.

Although Hale (1967) had noted it difficult to demonstrate regular seasonal cycles among Collembola, the species he discussed were from uniform climates. In South Australia, Greenslade (1974b) showed strong seasonality was often exhibited by epigaeic Symphypleona including species of Katianna, which were typically active through winter and replaced by Corynephoria spp in summer, commenting that such seaonality could be expected in areas with a mediterranean climate.

In England, S. viridis is found in pastures in 9 months of the year from early spring to mid-winter, population maxima being recorded in summer (MacLagan 1932a). In South Africa, Australia and New Zealand the active stages are usually scarce to absent in summer and first appear in autumn, activity continuing through winter and into the following spring. Seasonal peaks in activity usually occur in late autumn/early winter and again in spring. (Davidson 1934; Evans 1937; Dumbleton 1938; Walters 1964; Wallace 1967; Dentener 1985). However, Dumbleton (1938) noted that in New Zealand, active stages could be present throughout the year in some localities if moisture conditions were favourable throughout summer.

Davidson (1933c) showed that the time of appearance and disappearance of

active stages of S. viridis in southern Australia was closely related to the rainfall. Using this parameter he defined the seasonal distribution of S. viridis throughout its range. However, he incorrectly predicted that the species would be scarce to absent during mid-winter in Tasmania "owing to the extended winter period". Population samples taken in Tasmania by Evans (1937) at West Devonport showed that although adults were scarce in winter young and older immatures were abundant, with active stages present from the beginning of April until mid-December.

Evans results are shown graphically in Fig. 1.2 the graph illustrates (a) the sudden increase in numbers at the end of May after hatching of eggs laid by the first generation; (b) the scarcity of adults in winter (due to low temperatures); (c) high total population in spring (associated with rising temperatures and moisture at the soil surface); and (d) the sudden reduction in numbers in mid-December which is associated with low rainfall, rising temperatures and rising saturation deficiency of the air (Evans 1937).

There are usually 4-6 generations of S. viridis annually, although the number may vary according to prevailing conditions (MacLagan 1932a, Evans 1937; Walters 1964; Dentener 1985). There is also a pronounced overlapping of generations in the field due to the irregularity of hatching of eggs and to the long period of sexual maturity over which individual S. viridis can lay eggs (Walters 1964).

FEEDING HABITS AND PEST STATUS OF COLLEMBOLA

(1) General

Collembola feed on a variety of material including fungal hyphae, bacteria, nematodes, dead or decaying plants, pollen grains, spores, unicellular algae, live plant material, faecal matter, and live and dead animal material (Paclt 1956; Poole 1959; Christiansen 1964; Gilmore 1970; Greenslade and Greenslade 1983; Fjellberg 1985). Although Hale (1967) suggested Collembola may be selective feeders as they only digested fungi and bacteria on ingested residues and excreted the remainder, a number of subsequent food preference studies indicated that Collembola are unspecialised feeders (Petersen 1971; McMillan and Healy 1971; Anderson and Healy 1972; McMillan 1975, 1976). However, more recent studies have shown that euedaphic Collembola can be selective in their food requirements. Species of Onychiurus show a distinct preference for some fungi (Visser and Whittaker 1977; Parkinson et al 1979; Curl 1982; Newell 1984). This has been attributed to differing olfactorial responses to volatile compounds released by different fungi (Bengtsson et al 1988). Laboratory studies on the feeding preferences of O. armatus by McMillan (1976) showed that many species of yeasts and fungi are favourable foods, but some were significantly more favoured. Although acknowledging that laboratory food preferences may be different to the field situation, he concluded that the ability of species to diversify its food source may be of significance for survival during times when certain foods are

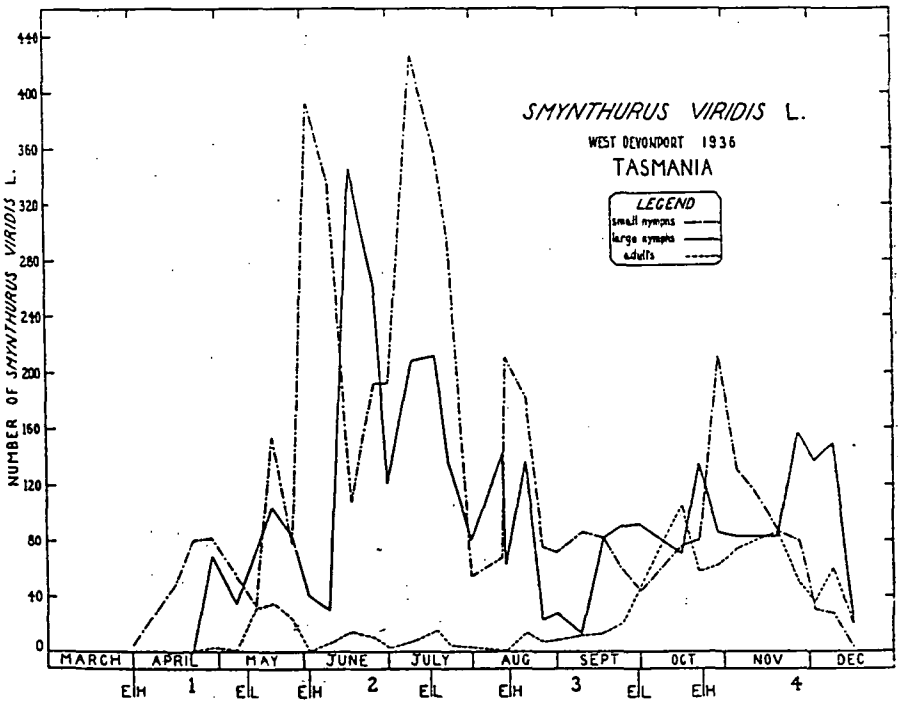


Fig 1.2 Weekly population estimates of S. viridis at West Devonport (1936) (Evans 1937).

unavailable.
On plants most Collembola are probably best defined as secondary feeders, grazing on dead and decaying plant material or associated microorganisms but do not feed on live plant material. In their role as decomposers Collembola may aggregate around decaying plant material in large numbers, but others may be attracted to live plants to feed on exudates or their associated microflora (Macnamara 1924; Wiggins et al 1979; Curl 1982), or to graze fungi directly growing on leaves or in the rhizosphere (Harding and Stuttard 1974; Wiggins et al 1979; Curl 1982).

In doing so it is quite possible that many Collembola could become associated with direct damage to the roots and leaves of live plants after feeding on damaged or decaying plant parts, following damage by some primary agent (e.g. fungal pathogen or insect pest). This suggests that many species may have been erroniously included on the lists of injurious Collembola occurring in the northern hemisphere by Collinge (1909, 1910), Theobald (1911), Mills (1930), Folsom (1933) and Paclt (1956). It also seems that the inclusion of a species on an earlier list often resulted in inclusion on later lists without question. Womersely's (1939) review of Australian Collembola included a list of 69 supposedly injurious species which seems to have been largely on the list of Folsom (1933). However, Womersley's list is misleading as it contains only 12 species which were actually referred to as injurious, the remainder being found in situations where they could have been damaging, or because they were present in large numbers rather than injurious (e.g. Hypogastrura viatica (Tullberg) was listed as being useful in England for cleaning sewage filters).

Overall, the breeding activities of most Collembola can be considered as beneficial as they play a role in the breakdown and decomposition of organic matter, nutrient cycling (Butcher et al 1971) and in pollination (Kevan and Kevan 1970). Furthermore, the mycophagal activities of many species may assist spore dispersal (Curl 1982), stimulate fungal growth Hanlon and Anderson (1979) and at low densities may increase plant yield and nutrient uptake (Finlay 1985).

(2) Feeding habits and pest status of euedaphic species.
The cosmopolitan species Proisotoma minuta Tullberg, P. tenella Reuter and Folsomia fimetaria L. have all been associated with damage to plant bulbs or roots (Paclt 1956). However, species of Onychiurus are more frequently associated with root damage to a much wider variety of plants both in Australia (Wallace and Mackerras 1970; Hamilton 1976) and overseas. The plants attacked overseas include a range of vegetables (Mills 1930; Theobald 1911; Folsom 1933; Brown 1954; Paclt 1956; Edwards 1962; Scott 1964; Getzin 1985), ornamentals (Collinge 1909; Folsom 1933; Paclt 1956; Scott 1964) and sugar cane (Spencer and Stracener 1929, 1930). In Europe, changes in sugar beet husbandry since 1960 have resulted in Onychiurus spp. now being regarded as important pests of the

seedling stage of this crop (Brown 1983) and much work has been done on factors which may stimulate population increase, on cultural factors which may predispose seedlings to attack and on control measures (Winner and Schäufele 1967; Heijbroek 1971; Heijbroek et al 1980; Baker and Dunning 1975; Grègoire-Wibo 1980; Brown 1983, 1984). Onychiurus has also been recorded as a pest of sugar beet in the Western United States (Lange 1987).

Feeding studies suggest that Onychiurus and other euedaphic species are mainly mycophagous (Harding and Stuttard 1974) and are attracted to the rhizosphere where fungi are readily available (Bowen and Rovira 1976; Curl 1982). As a result, large Onychiurus populations may build-up (Farahat 1966), particularly around stressed plants, due to the increase in root exudates enabling an increase in rhizosphere microflora (Curl 1982). This led Lawrence (1979) to question whether such species were actually the primary cause of root damage, or whether their attacks were on already weakened or damaged plants. The relationship between the rhizosphere, the associated microorganisms and mycophagous Collembola are complex and were discussed by Curl (1982) and Finlay (1985) and can result in both beneficial and detrimental affects on plant growth. Collembola may assist in transporting fungal spores and bacteria through the soil to the rhizosphere, but feeding on pathogenic fungi may also result in a decrease in inoculum potential (Curl 1979, 1982). There is also evidence that mycophagous soil Collembola may have either an inhibitory or stimulating affect on michorizal associations of plant roots depending on grazing pressure (Hanlon and Anderson 1979; Bengtsson and Rundgren 1983; Finlay 1985). This may affect plant yield and nutrient uptake, low grazing densities of Collembola causing increased plant yields and nutrient uptake by optimizing the growth of external mycelium, however, these beneficial affects may be negated at higher collembolan densities (Finlay 1985). Although the evidence shows that the feeding activities of Onychiurus in the rhizosphere can result in occasional (and often severe) damage to plant roots, it is possible that the many instances of damage to crops such as sugar beet are associated with poor cultural practice (Heijbrock et al 1980). For instance, Curl (1982) discusses the effect of pesticides on non-target organisms, suggesting the pesticides may inhibit or stimulate fungal growth and may indirectly affect pathogenic fungi as a result of affects on associated microflora. He postulates that such imbalances in microhabitats could result in plants, particularly those under stress, becoming more susceptible to disease and invertebrate attack.

(3) Feeding habits and pest status of hemiedaphic species

Studies indicate that most hemiedaphic species feed on decomposing plant litter and associated microorganisms particularly fungi, and although some are predominantly mycophagous, plants such as lichens, algae and bryophytes may be food sources for some species (Harding and Stuttard 1974). Although collembolan mycophagy is mainly associated with the

fungi of plant debris, several species have been recorded as pests in mushroom cultures both overseas (Theobald 1911; Mills 1930; Folsom 1933; Maynard 1951; Paclt 1956) and in Australia (Womersley 1939; Wallace and Mackerras 1970; Hamilton 1976; Clift 1983).

The species involved are mainly from the genus Hypogastrura but also include species of Lepidocyrtus (Folsom 1933; Paclt 1956). According to Clift (1983) these Collembola were often significant pests when the mushrooms were grown in outdoor ridge beds, but with the advent of purpose-built houses, pasteurization of compost and the use of peat in the casing layer, they are no longer of any significance. Theobald (1911), Mills (1930), Folsom (1933), Womersley (1939) and Paclt (1956) also include Hypogastrura species as damaging to a variety of vegetables and ornamentals. However, as Hypogastrura species often aggregate in huge numbers on the soil surface, and feed predominantly on microorganisms, the presence of such large numbers in association with damaged plants makes it questionable whether Hypogastrura have often been wrongly implicated in causing primary damage, or whether they are feeding on already damaged plants. Theobald (1911) in discussing damage to cabbages by Hypogastrura purpurescens (Lubbock) (= Achorutes purpurescens Lubbock) refers to the large numbers of this species around cabbage roots, noting that the outer cortex of roots were attacked only on unhealthy plants, the damage to healthy plants being slight. Few other hemiedaphics have ever been reported as damaging but those that have included the comopolitan species Isotomurus palustris Mueller reported as injurious to roots of sugar cane (Folsom 1933), tobacco seedlings (Splendore 1912) and mangolds (Davies 1925); Owen and Owen (1958) recorded Entomobrya unostrigata Stach as damaging seedling cotton leaving numerous holes in some cotyledons and causing partial to complete destruction of others; also, the base of some cotyledons were damaged while still in the seed coat. Scott (1964) reports damage by this species to lettuce and tomato seedlings by rasping and notching the stems and leaves.

Species of Entomobryidae have also been recorded as household pests occasionally entering houses in large numbers, probably in search of cool moist conditions during exceptionally dry periods (Marlatt 1896; Scott 1962, 1966; Ebeling 1975; Arnaud and Davies 1980). The cosmopolitan E. atrocincta Schoett is recorded by Scott (1966) as a pest of dried milk powder.

(4) Feeding habits and pest status of epigaeic species

(i) Main food sources

The main food sources for epigaeic species include a variety of microflora associated with live and dead plant material (Greenslade and Greenslade 1983; Marshall 1978). Pollen may also be an important food source for some species (Kevan and Kevan 1970; Ellis 1978; Marshall 1978). A minority of species which include S. viridis, may also feed on

live plant material, and together with S. viridis have been recorded as pests.

(ii) Species recorded as pests and their food plants.
The garden springtail, Bourletiella hortensis (Fitch), (or its synonyms), has been frequently recorded as damaging to a wide range of vegetables, cereals and ornamentals (particularly in their seedling stage), in Europe (Theobald 1911; Macnamara 1924; Davies 1925, 1926; Paclt 1956; Edwards and Heath 1964; Bevan 1965), Canada (Marshall and Ilnytzky 1976; Marshall 1978), Brazil (Paclt 1956), Japan (Honma 1988) and North America (Fink 1914; Mills 1930; Folsom 1933; Maynard 1951; Paclt 1956). A related species, recorded as Bourletiella arvalis (Fitch) (or synonyms), has also been recorded as damaging the leaves of vegetables and other plants in North America and Europe (Mills 1930; Folsom 1933; Paclt 1956) and together with B. hortensis has been recorded as attacking seedling cruciferous crops in New Zealand (Cleland 1955). In Australia, Womersely (1939) included Katianna australis Womersley, K. ornata Womersely, Parakatianna obscura Womersely (= K. obscura) in his list of injurious species as damaging subterranean clover. He also listed two species of Deuterosminthurus together with Bourletiella arvalis as damaging to pastures and B. hortensis as damaging to crops and pastures. Wallace and Mackerras (1970) also record Katianna australis as feeding extensively on clovers and other legumes, although this observation may have been based on the record of Womersley.

Until S. viridis was recorded as a major pest in Australia, its feeding habits in European countries where it had never been regarded as a pest, appear to have been mostly overlooked (Davies 1928; MacLagan 1932a). S. viridis is polyphagous in habit and attacks representatives of the families Urticaceae, Cruciferae, Polygonaceae, Compositae, Gramineae and Leguminoseae (MacLagan 1932a). A list of host plants was presented by Holdaway (1927) and Walters (1964) listed 60 species of food plants previously recorded in the literature together with an additional 38 host species noted by him in South Africa. Fungi, algae and mosses may also form an important part of the diet. It also feeds on cast skins, dead companions and eggs of its own and other species (Walters 1964). Although omniverous, the species shows a decided preference for the Leguminoseae, particularly clovers and lucerne (Medicago sativa) if these are available. In England it thrives best on Trifolium species especially T. repens (white clover) and its varieties (MacLagan 1932a). MacLagan (1932b) also demonstrated a positive correlation between percentage composition of Leguminoseae in the herbage and the population density of S. viridis in the field. In South Africa, S. viridis showed a marked preference for lucerne in a mixed lucerne/subterranean clover (T. subterraneum) pasture. In Australia, most economic damage occurs in pasture on lucerne, subterranean clover and white clover (Holdaway 1927; Evans 1937; Pescott 1937; Wallace 1954a) and in New Zealand on white clover (Pottinger et al 1985; Gatland 1988).

Certain clovers such as T. arvense and T. angustifolium are attacked less severely than others, probably due to their less succulent character and pubescent covering (Davidson 1934). Davidson (1933b) tested nine varieties of lucerne, but all were attacked by S. viridis. The variety, 'Hairy Peruvian', suffered less than the other varieties early in the season due to its upright habit during early growth, but was attacked more heavily later in the season as the population of S. viridis increased.

S. viridis has been known to attack turnips, mangolds, barley, oats, wheat and grasses (Davies 1928) and can therefore exist on other crops apart from clovers and lucerne in the rotation, and thus tide over arable conditions and be present when the field is laid down to clover or grass. Damage is particularly severe on young plants (Swan and Lower 1951) and, in the market garden, carrots, turnips and lettuce are attacked mainly at the seedling stage (Swan 1940) as are most vegetables and weeds (Edwards 1950).

The only plant factor which seems to inhibit attack is morphological structure: plants with a broad leaf expanse with few veins, such as capeweed (Arctotheca calendula (Druce) are preferred by S. viridis; narrow-leaved species with close-set veins, as in grasses, are less liable to attack. Thus, infestations are favoured by the presence of broad-leaved plants (such as capeweed) which provide the insect with food and shade (MacLagan 1932a). When grown in close proximity to weedy land, clovers, lucerne and vegetables seem more likely to be attacked by S. viridis (Jenkins 1956).

Studies by Gatland (1988) showed that S. viridis feeds during the day and night with significantly less feeding at night. At night, specimens occurred in larger numbers on the soil surface than during the day, apparantly preferring to feed on the uppermost layers of clover leaves.

(iii) Type of injury

S. viridis feeds with a bite which is a combination of a gnawing (or rasping) and chiselling action of the mandibles and maxillae. Young immatures eat small holes through the epidermis giving the leaf a speckled appearance; older nymphs eat more vigorously and the resultant holes through the upper or lower epidermis are gradually enlarged and the mesophyll completely removed. Leaves damaged by older nymphs show characteristic window-like openings (Swan 1940). In an advanced stage of attack, a skeletonising effect results with only veins and ragged portions of the epidermis remaining. The co-existence of S. viridis and the red-legged earth mite Halotydeus destructor (Tucker) in pasture frequently complicates the appearance of damage to clover, but each type of damage can be distinguished: H. destructor sucks sap but doesn't remove any solid plant tissue and the leaves have a blended appearance,

but remain opaque; leaves attacked by S. viridis have transparent openings (Birks 1969).

S. viridis attack on clover can retard further growth and dwarf plants (Walters 1964) but it is doubtful whether actual death of plants ever results (Pescott 1937). Early feed is stunted and contains little food value when seedlings are attacked (Newman 1927b). Excreta of S. viridis foul the pasture, reducing the palatibility of the plants to stock (Dumbleton 1938; Walters 1964; Birks 1969; Pottinger et al 1983).

Although Womersley (1939) listed a number of Symphypleona other than S. viridis as injurious to pasture, he did not specify the type of damage. Fink (1914) described the injury to cucurbits by a species that was probably Bourletiella hortensis as being in the form of irregular holes sometimes eaten completely through, or with a thin transparent layer of epidermis separating the upper and lower surfaces. Bevan (1965) discussed damage to conifer seedlings as occurring at germination and seed emergence, with cotyledons and hypocotyl suffering damage. Cleland (1955) described damage by B. hortensis and B. arvalis to seedling crucifers stating that injury began immediately after the shedding of the seed shell and before the cotyledons opened. In many cases cotyledons were completely removed, damage to cotyledons up to the 4-leaf stage appearing as a slight scalloping on the leaf edge or as small pits of damaged tissue on the leaf. After passing the 4-leaf stage, Cleland noted that plant growth was usually able to compensate for any further attack.

ECONOMIC INJURY

As a group few Collembola have been recorded as injurious. Of those that have been recorded as damaging, S. viridis (although not regarded as a pest in Europe), is by far the most economically important, causing extensive damage to leguminous crops and pasture in South Africa, New Zealand and in Australia where populations as high as 60,000/m^2 have been recorded (Wallace and Mackerras 1970). Although S. viridis is regarded as a serious pest in these countries comparatively few evaluations of the loss of pasture productivity attributable to S. viridis infestations have been carried out. Walters (1964) gained increases in average yield per plot of 143.7% lucerne, 12.45% subclover, and 29.16% grasses in lucerne/subterranean clover/grass pastures following a spray application of mercaptothion. Similar results were obtained by Davidson (1933b) who found a marked increase in yield of infested lucerne pastures by spraying with lime-sulphur. O'Neil (1958) reported on an unreplicated experiment in South Australian pastures in which he claimed that control of S. viridis and red-legged earth mite (H. destructor) with a malathion/DDT spray almost doubled the stock carrying capacity, increased the proportion of clover at haycutting from 15% to 60%, and increased the quantity of clover seed harvested by almost 400%. Wallace and Mahon (1963) measured the yield of established, sown pastures after applying a

malathion/DDT spray to control S. viridis and H. destructor and obtained an average response of 9.7 kg/ha of extra dry matter in the spring. To consume this, they suggested that the stocking rate should be increased by an average of 0.6 sheep per ha. In New Zealand, Pottinger et al (1985) recorded pasture production loss of 18 and 30% over 6 week intervals, when mean catches of 500-800 S. viridis were taken in a sweep net per 6m of pasture swept. They also stated that increases in pasture production over a 6 week period following the application of insecticides were worth up to 7 times the treatment costs.

A recent estimate of the annual losses of potential output to the Australian Wool industry for pest, weeds and diseases ranked S. viridis together with H. destructor and the blue-green aphid, Acyrthosiphon kondoi Shinji, as having the highest impact, causing an estimated $238 million loss to the industry annually (Anon 1988). It should be noted, however, that these estimated losses were sustained mainly in annual legume pastures (medics and clovers) and were based on the potential of these species to reduce the amount of seed set by up to 60%, thereby reducing the sward legume in the following season. In Tasmania and New Zealand the situation differs as most losses attributable to S. viridis are sustained in perennial pastures grazed mainly by dairy cattle (Ireson 1981; Pottinger et al 1985). Wallace and Mahon (1963) considered that the economic importance of S. viridis and H. destructor may sometimes have been exaggerated as a result of pastures being understocked. They also discussed insecticide treatment as being fully justified only in highly productive (established) clover/medic pastures but not low yeilding pastures. However, they acknowledged the need for treatment of newly establishing pastures (and field crops).

CONTROL

(1) Cultural and mechanical methods

(i) Euedaphic species

Cultural methods have been used in an integrated programme for control of Onychiurus in sugar beet (Heijbroek et al 1980; Dunning and Baker 1977). These include the preparation of a compacted seed bed which is repellant to Onychiurus (Heijbroek 1971; Didden 1987) and the avoidance of clover and grass crops in rotation which can favour the build-up of Onychiurus. As weeds create an alternative food supply between rows, avoidance of herbicides in favour of mechanical weed control if necessary, has also been used. Reduction in overall pesticide use is an approach now being favoured, as usage can lead to a reduction in predators which can favour the build up of Onychiurus. Molasses have also been applied between rows to stimulate fungal growth as an additional food source for Onychiurus (Heijbroek 1971; Heijbroek et al 1980).

(ii) Surface-active species

Sweeping infested areas with tarred sacks was a method described by Davies (1926) for reducing populations of B. hortensis in mangold crops.

A similar method using tarred screens or shallow trays was also recommended as a method of controlling S. viridis in pastures (Newman 1927b).

Burning vegetation can significantly reduce collembolan populations (Vlug and Borden 1973; Metz and Dindal 1975) and burning over paddocks infested with S. viridis has given good control (Newman 1927b; Birks 1969). Crop rotations seem to be of little value but, field crop infestations of S. viridis have often occurred in paddocks ploughed from pastures heavily infested by the pest (Withecombe 1978). Fallowing has been recommended as providing some control of S. viridis but such areas are usually re-invaded rapidly (Holdaway 1927; Newman 1927b; Birks 1969). Procedures which assist in the reduction of the moisture content of the surface layers of soil such as mulching, harrowing and rolling reduce population levels of S. viridis (MacLagan 1932b). However, ploughing does not destroy the eggs: the young insects hatch and readily emerge through the open soil (Davidson 1933b).

As grasses are less liable to attack from S. viridis than are leguminous plants, possibly due to the lower nitrogen content of the grass tissue, mixed pastures will suffer less than pure clover stands (Dumbleton 1938; Swan 1940). As Davidson (1934) pointed out, the clovers in a pasture of this type may be damaged in autumn, but the grasses afford adequate grazing, and in spring, clovers rapidly grow away from insect attack. A vigorous mixed pasture may present a less favourable habitat for S. viridis than a pure clover stand partly because a closed award may reduce the favourability of the soil for egg-laying and also because of prolonged periods of excess moisture, as dense pastures remain almost permanently wet during winter (Swan 1940). Walters (1964) considered that the feeding of S. viridis on grasses dominating a plant stand may result in lower fecundity and therefore lower populations and less damage in mixed pastures, compared to pure stands of lucerne or clover.

A number of studies show that grazing animals are an effective method of significantly reducing collembolan populations in pasture (King and Hutchinson 1976; King et al 1976; Purvis and Curry 1978). Spafford (1921) and Davidson (1933b) discuss close grazing as an effective control measure for S. viridis, heavy stocking resulting in trampling and opening of the sward rendering the species more susceptible to heat and dryness, although trampling does not destroy S. viridis eggs (Dumbleton 1938; East and Pottinger 1983). More recently Pottinger et al (1985) stated that cattle stocking rates exceeding 300/ha/day during May-July in New Zealand resulted in S. viridis populations taking 4 months to recover to pre-grazing levels. Lactating cows stocked at 60-112/ha/day from August - December depressed S. viridis for shorter periods. However, there was no indication as to whether the possible effect of other factors (such as weather) on population decreases and the amount of time taken to recover to pre-grazing levels was considered.

(2) Biological control

(i) Acarine predators

Mites are considered to be the most important predators of Collembola and include mesostigmatid mites from the families Veigaiaidae, Neoparasitidae, Macrochelidae, Pachylaeleptidae, Phytoseiidae and Parasitidae and the trombidiform families Cunaxidae and Bdellidae (see reviews by Paclt 1956 and Christiansen 1964 for main references). Bhattacharyya (1963) noted Pergamasus spp. (Parasitidae) as being among the most important acarine predators in palearctic soils, Collembola being among their main food sources (Harris and Usher 1978). Perhaps the most significant group of collembolan mite predators, however, are the Bdellidae. Two species, the pasture snout mite Bdellodes lapidaria (Kramer) and the spiny snout mite, Neomolgus capillatus (Kramer) are particularly important in S. viridis biological control programmes in South Africa and Australia (Wallace 1967, 1974a, 1974b; Wallace and Walters 1974). However species are not host-specific and feed on a range of collembolan species (Wallace 1974a; Wallace and Walters 1974; Wallace and Mahon 1976). Such non-selective feeding behaviour is considered an ideal attribute for a biocontrol agent, as it is able to maintain itself on other prey species during periods when a more favoured food source may be scarce (Wallace and Walters 1974).

The predatory mite, Bdellodes lapidaria (Kramer) (Acari : Bdellidae) was first discovered attacking S. viridis in pastures in Western Australia in 1931 (Newman and Womersley 1932, Womersley 1933a). More detailed studies by Currie (1934) showed that B. lapidaria was able to control S. viridis populations in areas where the predator was originally discovered and his observations were supported by those of Jenkins (1935) and Norris (1938) in Western Australia. Currie (1934) described methods of collecting and transporting B. lapidaria and consignments were sent to South Australia, Victoria and Tasmania for release, however, B. lapidaria was subsequently found to occur naturally in each of these States. In South Australia, there was no evidence that the predator was controlling S. viridis in the pastures where artificial liberations were made (Swan 1940), although Pescott (1937) considered that some reduction in numbers had occurred in one Victorian district where the predator was active. In Tasmania, Evans (1937, 1939) reported that S. viridis was being controlled by B. lapidaria in some areas where the predator occurred naturally, but no effect was noticed where artificial liberations had been made, suggesting that in many areas S. viridis could thrive but not B. lapidaria.

Although there was some disagreement as to whether B. lapidaria could exert effective control over S. viridis, Norris (1938) was able to correlate a fall in S. viridis numbers with an increase in predator numbers in Western Australia. Further work by Wallace (1954a) showed that S. viridis was not only resistant to DDT sprays but numbers actually increased, presumably as a result of the elimination of B. lapidaria which was susceptible to DDT treatment.

Wallace (1967) subsequently carried out a detailed study of the predation of S. viridis by B. lapidaria at sites in Western Australia. He demonstrated a significant predator-prey relationship between the two species with analyses indicating that when B. lapidaria numbers early in the season were greater than $20/m^2$, this was sufficient to prevent any outbreak of S. viridis later in the same season. If predator density was less than $10/m^2$, S. viridis numbers increased to outbreak proportions.

B. lapidaria was subsequently introduced into South Africa from Australia and successfully established, preliminary data indicating it would be capable of influencing S. viridis populations under South African conditions (Wallace and Walters 1974).

Despite these results, reports still suggest that, in some areas, B. lapidaria is not always effective. Birks (1969) and Hopkins (1983) state that although considerable importance is sometimes attached to B. lapidaria in controlling S. viridis, it is mostly ineffective in South Australia. In New Zealand, Pottinger (1983) stated that severe infestations of S. viridis had occurred in pastures not treated with pesticide for over a decade, therefore naturally occurring predators (such as B. lapidaria) were not always effective. A preliminary study by Dentener (1985) in New Zealand showed that high B. lapidaria activity coincided with low numbers of S. viridis and other sminthurid species and vice versa. However, the data were obtained from pitfall trap catches and therefore were only a measure of species activity and not population density. It was acknowledged that further work would be necessary to determine if B. lapidaria did have a significant controlling influence on S. viridis in some New Zealand pastures.

Womersley (1933b) published the first account of the bdellid mites of Australia. Atyeo (1963) then reviewed the Australian fauna using limited material. As part of a CSIRO project on the biological control of S. viridis with predatory mites, extensive surveys of southern and north-western Australia in 1962 and 1964 were carried out and added considerably to the knowledge on the taxonomy, biology and distributions of Australian Bdellidae (Wallace and Mahon 1971, 1972, 1976).

Comparison of the bdellid fauna collected in these surveys with that of Europe and North Africa indicated some genera in southern Australia were represented by a considerably smaller number of species (Wallace 1974a).

It was therefore postulated that among the many European species there may be other bdellid predators that would be useful biological control agents in Australia. Subsequent surveys by Wallace (1974a) in Europe and North Africa showed that the two most common bdellids were B. lapidaria and another species, Neomolgus capillatus (Kramer) which was not present in Australia. N. capillatus was found to have an affinity for S. viridis

and therefore was considered a potentially useful predator for Australia. A strain which was found to be tollerant of dry areas was imported and eventually established in Western Australia. Parallel introductions of another predator Anystis salicinus (L.) were also carried out (Wallace 1974a), primarily for control of red legged earth mite (H. destructor) and blue oat mite (Penthaleus major Dugès), however, the species was also known to prey on S. viridis. Both species have subsequently been introduced into South Africa for control of S. viridis (Wallace 1974a; Meyer and Uekermann 1987).

Preliminary observations reported by Wallace (1981) suggested that both N. capillatus and A. salicinus could be successful biological control agents in Western Australia, however, as their rate of spread is extremely slow, he stated that a redistribution programme from established sites to assist the rate of spread, would be necessary. The commencement of this programme was reported by Michael (1989).

(ii) Non-acarine predators

A large number of non-acarine predators of Collembola have been recorded and these include Carabidae (MacLagan 1932a; Paclt 1956; Choudhuri 1962; Ernsting and Joosse 1974; Manley et al 1976; Ernsting et al 1977; Ernsting and Jansen 1978; Thiele 1987; de Ruiter et al 1988), Staphylinidae (Holdaway 1927; MacLagan 1932a; Paclt 1956; Choudhuri 1962; Christiansen 1964; Manley et al 1976), Coccinellidae (MacLagan 1932a; Paclt 1956), Teleophoridae (MacLagan 1932a), Anthicidae (Paclt 1956), Elateridae and Cantharidae (Manley et al 1976) from the Coleoptera, Anthocoridae and Capsidae (MacLagan 1932a) from the Hemiptera, Formicidae (Holdaway 1927) from the Hymenoptera, Corydyloridae (Walters 1966) from the Diptera, Forficula auricularia (MacLagan 1932a) from the Dermaptera, Pseudoscorpionida (Christiansen 1964; Ernsting and Joosse 1974; Johnston and Wellington 1980), Chilopoda (Christiansen 1964, 1971, Sunderland 1975; Manley et al 1976) and arachnids from a range of families (MacLagan 1932a; Paclt 1956; Christiansen 1964, 1971; Walters 1964; Manley et al 1976; Gatland 1988).

MacLagan (1932a) listed 14 insect and 11 spider predators of S. viridis and considered that staphylinid beetles and spiders of the family Thomisidae were the most numerous and efficient predators. However, for observations conducted in the laboratory (as MacLagan's were), little reliance can be placed on the results with regard to the actual field situation.

Scatophaga stercoraria(L.) (Diptera : Cordyluridae), the yellow dung fly, preys on S. viridis in South Africa (Walters 1966). Walters considered that the fly may be an important predator in restricting S. viridis as it occurs in large numbers in infested pastures in South Africa.

Observations on arachnid predators of S. viridis in New Zealand by

Gatland (1988) showed that the majority of predaceous species were polyphagous. Although 8 species fed on S. viridis, only species of Theridiidae and the wolf spider, Lycosa hilaris had some potential as control agents. These, however, appeared unable to regulate S. viridis populations.

(iii) Nematodes

The susceptibility of a range of arthropod species to parasitism by nematodes is widely known (Poinar 1979). Use of the entomophilic nematode Steinernema carpocapsae as a bio-control agent for Onychiurus in sugar beet crops was investigated by Edwards and Oswald (1981). Field trials involving the application of aqueous suspensions of N. carpocapsae to sugar beet rows were shown to significantly reduce populations of Onychiurus, further expanding the potential of Nematodes as useful biological control agents

(3) Chemical control

(i) Susceptibility of Collembola to pesticides

A comprehensive review on the effect of pesticides on Collembola is given by Edwards and Thompson (1973) who provide a tabular summary with references of the effects of organochlorine, organophosphate and carbamate formulations.

Collembola vary considerably in their susceptibility to pesticides, (Edwards and Thompson 1973; Martin 1975, 1978; Gregoire-Wibo 1981), however, they are generally less susceptible than mites and many species are completely unaffected except by very large doses (Edwards and Thompson 1973; Tomlin 1975; Thompson and Gore 1972). For instance, many Collembola have been found resistant to DDT (Edwards 1965; Edwards et al 1967a; Klee 1971), the first record being by Hoffman and Merkel (1948). Other examples include Wallace (1954a, 1954b) who found DDT ineffective against S. viridis in pasture, as mentioned previously, Cleland (1955) who reported the failure of DDT to control Bourletiella spp. in cruciferous crops and Butcher et al (1969) who demonstrated the ability of F. candida to degrade DDT to DDE in laboratory cultures. Edwards and Thompson (1973) cite a number of references which show that the use of DDT generally has invariably resulted in increases in collembolan numbers due to a decrease in the number of predators which were susceptible to the pesticide. Other organochlorines such as lindane and aldrin have had variable effects and chlordane has generally decreased numbers of soil Collembola.

Results obtained with carbamate and organophosphate insecticides have also been variable. Edwards and Thompson (1973) cite a number of references reporting either an increase or decrease in collembolan populations following application of carbaryl. Seed furrow treatment with aldicarb was reported by Heijbroek (1971) and Heijbroek et al (1980) as giving adequate protection to sugar beet crops against attack

by Onychiurus. However, in other trials aldicarb has been reported as having no influence on Onychiurus (Edwards 1980). The organophosphate phorate was found to cause general reductions in populations of euedaphic Collembola (Edwards et al 1967b; Way and Scopes 1968) and chlorfenvinphos has been found to cause increases (Edwards et al 1968). Field studies on the effects of pesticides on surface-active Collembola in barley by Frampton (1988) showed that populations of 4 species of Symphypleona (Sminthurinus aureus (Lubbock), Sminthurinus elegans (Fitch), Jeannenotia stachi (Jeannenot) and S. viridis) were significantly reduced by the organophosphate fungicide pyrazophos and the broad spectrum organophosphate insecticide dimethoate. As well as dimethoate, a number of organophosphate chemicals are effective against S. viridis and are widely used for its control in pastures and field crops in Australia, New Zealand and South Africa (Bot et al 1976; Erlich 1980; Ireson 1981; Hopkins 1983, Sandow 1983; Pottinger et al 1985).

(ii) Chemical control of S. viridis

(a) Timing of pesticide applications

Pesticides are effective only against the active stage of the pest, the eggs being resistant. For control in pastures, State Departments of Agriculture recommend pesticide applications from 2-5 weeks after the opening rains in autumn. This is to enable maximum hatching of over-summering eggs. Furthermore, if sprays are timed correctly and applied before hatched S. viridis mature and reach the oviposition stage, this can prevent outbreaks later in the same season. The success of this control measure, however, depends on whether there is a definite autumn break followed by a synchronised hatch. If not, a follow-up spray may be necessary to control the S. viridis that may hatch after the first spray. Populations usually decrease naturally with the onset of cooler conditions by late winter but rise again to damaging levels in spring which may also necessitate pesticide application (Birks 1969; Erlich 1980; Ireson 1981; Hopkins 1983; McQuillan and Ireson 1987).

Pottinger et al (1985) give similar recommendations for heavily infested New Zealand pastures. They found no difficulty in obtaining control with pesticides, provided they were strategically applied in autumn from 2-6 weeks after the initial appearance of nymphs to prevent recruitment of first generation eggs. They also recommended spring applications if infestation levels are high enough. It has been recommended to mow or graze the pasture prior to spraying to enable maximum exposure of S. viridis to the pesticide (Davidson 1933b; Evans 1943; Erlich 1980), however, heavy grazing by stock may itself be a satisfactory control method (Evans 1943; Pottinger et al 1985).

S. viridis activity decreases by late spring or early summer when dry conditions level to the productions of oversummering eggs (Wallace 1967).

In field crops the seedling stage is particularly vulnerable to S.

viridis attack and relatively light infestations can cause serious losses, however, the crop can usually grow away from moderate infestations after establishment. Pesticide applications, therefore, are usually applied at germination prior to the emergence of cotyledons.

As there are always some survivors of pesticide application, these together with the occurrence of delayed hatching and re-infestation from surrounding areas enable the eventual build-up of S. viridis populations at treated sites.

(b) Chemicals used

A summary of the chemicals that have been used for the control of S. viridis in Australia is given in Table 1.4.

Table 1.4 Summary of published recommendations for the chemical control of S. viridis in Australia (rates are given in units used by the author).

Chemical	Application	Author
Gas-lime	7-10 cwt/acre	Summers (1900)
Lead arsenate	3lbs/40 gallons of water (21 day withholding period)	Newman (1927b)
Nicotine dust	3%	Davidson (1934)
Lime-sulphur	1/40 1/50-1/60	Evans (1943) Edwards (1950); Nicholls (1930); Davidson (1932c, 1933b); Pescott (1937); Swan (1940); Jenkins and Forte (1948).
BHC (lindane)	4% BHC in super-phosphate 2lb/acre 2lb/acre	Jenkins and Forte (1948) Swan and Lower (1951) Wallace (1954a); Wallace actually achieved poor control with BHC and was unable to explain this discrepancy with the results of previous workers. Birks (1969) and Hopkins (1983) note lindane

Table 1.4 (cont.) Summary of published recommendations for the chemical control of S. viridis in Australia (rates are given in units used by the author).

Chemical	Application	Author
		(BHC) as not being effective against S. viridis.
Parathion	1/4 oz. (ai)/acre	Anon. (1955); Jenkins (1956)
	1/2- 1 oz. (ai)/acre	Wallace (1954b)
	1/2 oz. (ai)/acre	Anon (1957)
Maldison (Malathion)	1/2- 1 oz. (50% ai)/acre often applied as a topdressing with superphosphate and with 4 fl. oz. of 25% DDT emulsion to control a combined infestation of S. viridis and the red-legged earth mite, Halotydeus destructor (Tucker))	Walker (1956, 1957) Jenkins (1956, 1957) Johnston (1960) Anon (1957)
	2-4 fl. oz (50% ai)/acre (140-280m/ha)	Anon (1973b)
Dieldrin	4-8 oz (ai) acre	Jenkins 1956
Azinphos-ethyl (Gusathion)	1/2 oz. (ai)/acre	Johnston (1960)
Phorate	1 oz/acre	Wallace (1963) (adverse effect on bdellid predators noted)
Phosmet (Imidan,	5 oz. 15% emulsion/acre	MacFarlane (1967)
Imicide, Imidine)	3.5 - 5 fl. oz. 15%/acre	Birks (1969); Anon. (1973b)
Maldison	4 fl. oz/acre 96% ai)	Birks (1969)
Dimethoate	0.3-0.5 oz/acre (40% ai)	Birks (1969)
Azinphos-ethyl	1/2 oz (40% ai)	Birks (1969)

Table 1.4 (cont.) Summary of published recommendations for the chemical control of *S. viridis* in Australia (rates are given in units used by the author).

Chemical	Application	Author
Methidathion	1/2 oz (40% ai)	Birks (1969)
Omethoate	1/2 oz (50% ai)	Birks (1969)
Azinphos-ethyl	80-100 ml/ha (40% ai)	Erlich (1980)
	80-90 ml/ha (40% ai)	Sandow (1983)
	90 ml/ha (40% ai)	Anon (1987)
Carbaryl	220-350 g/ha (80% ai)	Erlich 1980
	130 g/100 L	Anon 1987
Chlorfenvinphos	550 ml/ha (50% ai)	Erlich 1980
	850 ml-1 l/ha (50% ai)	Anon 1987
Chlorpyrifos	70 ml/ha (50% ai)	Erlich 1980; Hopkins 1983; Anon 1987
Demeton-S-methyl	300 ml/ha (25% ai)	Erlich 1980
Dimethoate	70-100 ml/ha (30% ai)	Erlich 1980; Sandow (1983)
Dimethoate	55-85 ml/ha (40% ai)	Erlich 1980; Anon (1987)
	60 ml/ha (40% ai)	Sandow (1983)
	50 ml-100 ml/ha (40% ai)	Hopkins (1983)
Formothion	140-170 ml/ha (25% ai)	Erlich (1980)
Maldison	280-600 ml/ha (50% ai)	Erlich (1980)
Maldison (ULV)	300 ml/ha (1.18 kg/l)	Erlich (1980); Hopkins (1983)
	210 ml/ha	Sandow (1983)
Methidathion	90 ml/ha (40% ai)	Erlich (1980); Anon (1987)
	100 ml/ha (40% ai)	Hopkins (1983)
Omethoate	50 ml/ha (58%)	Erlich (1980); Hopkins (1983); Sandow (1983); Anon (1987)

Table 1.4 (cont.) Summary of published recommendations for the chemical control of S. viridis in Australia (rates are given in units used by the author).

Chemical	Application	Author
Parathion	140 ml/ha (50% ai)	Erlich (1980)
Phosmet	250-350 ml/ha (15% ai)	Erlich (1980); Hopkins 1983; Sandow (1983); Anon 1987

Because of the persistance of organochlorine chemicals in the environment their use has gradually been phased out in Australia and none are registered for control of pests in crops or pasture in any Australian State with the exception of lindane, which is still being used in Victoria subject to restrictions. However, it is anticipated that all agricultural use of lindane in Australia will be phased out by June 1990 (Terauds pers. comm.). Lindane, however, has never been registered for control of S. viridis. The systemic organophosphates demethoate (Rogor), demeton and demeton-S-methyl (Metasystox) have been found to control S. viridis when applied as a seed dressing prior to sowing (Wallace 1961; Birks 1969). Demeton-treated seedlings were found toxic to S. viridis for up to 11 weeks after sowing whereas toxicity was lost in the demeton-S-methyl treatment after about 7 weeks. Although subterranean clover, peas and lucerne can be treated, the germination of oats and barley is impaired. Furthermore, the treatment has been found detrimental to seeds inoculated with Rhizobium cultures (Birks 1969).

Bot et al (1976) lists maldison and omethoate as the chemicals used for control of S. viridis in South African pastures. In New Zealand, a number of field trials on chemical control of S. viridis in pastures have been reported (Townsend et al 1979; Pottinger et al 1983, Wrenn et al 1984a, 1984b; Pottinger et al 1985). Until 1983 maldison was the only chemical registered for control of S. viridis in New Zealand even though earlier field trials by Townsend et al (1979) had shown that phosmet and omethoate gave overall better control than maldison, with omethoate generally superior to phosmet 15 or more days after treatment. Further trials by Wrenn et al (1983) showed that fenitrothion, dimethoate, chlorpyrifos, diazinon, omethoate and phosmet all gave longer periods of control than maldison. Another chemical, oxamyl, was only comparable to maldison in effectiveness and lacked persistency. Bioassay tests showed that the residuality of dimethoate , chlorpyrifos and fenitrothion on treated foliage was one of the reasons for their increased effectiveness. Wrenn et al (1983) report that dimethoate and fenitrothion were registered for control of S. viridis in New Zealand following the completion of these trials. Additional studies by Wrenn et al (1984b) showed that granular formulations of diazinon, chlorpyrifos, fenitrothion

and, another chemical, isazophos, gave levels of control equal to or better than e.c. formulations.

Trials by Pottinger et al (1985) with maldison, diazinon, dimethoate, chlorpyrifos, fenitrothion and isazophos (applied as sprays and granules) showed that applications 2-4 weeks apart were no more effective than single applications. They also showed that all pesticides, including those with the shortest residuality (maldison and diazinon), gave extended periods of control from May until October if applied in autumn 2-6 weeks after the appearance of nymphs. This contrasted with spring applied treatments which were effective from 2-9 weeks depending on the residuality of the product used.

(iii) Chemical control of other collembolan pests

In Europe a number of pesticides have been used effectively to control root-feeding Onychiurus in sugar beet crops. These include the organochlorine lindane, the carbamates carbaryl (as a seed treatment), aldicarb (as a seed furrow treatment) (Heijbroek 1971; Heijbroek et al 1980) and carbofuran (as a seed furrow treatment) (Brown 1985). In North America, Getzin (1985) also found carbofuran to be an effective seed furrow treatment for control of Onychiurus in spinach. Although Scott (1964) reported that dieldrin was used as an effective control for Onychiurus (either in granular form or as a seed treatment) and Entomobrya unostrigata Stach (as a foliar spray) on a range of field crops in California, poor control was obtained by Heijbroek (1971) and Baker and Dunning (1975) in Europe using dieldrin against Onychiurus in sugar beet. In New Zealand, Cleland (1955) obtained satisfactory control of Bourletiella spp. in cruciferous crops using a lindane spray (1/2 lb (16% a.i.)) per 100 gallons of water). In England, Bevan (1965) reported good control of Bourletiella hortensis (Fitch) (referred to as B. signata (Nicolet)) in nursery coniferous seedlings (Pinus contorta) was achieved using malathion (1 1/2 pints a.i./100 gallons of water/acre). The organochlorines aldrin, DDT and BHC were also tested as surface treatments, but none gave an adequate degree of control. In Canada, the organophosphates diazinon, fonofos, malathion, and the carbamate oxamyl were all effective in controlling B. hortensis on conifer seedlings (western hemlock and sitka spruce) in nursery trials (Marshall and Ilnytzky 1976).

In Australia, diazinon has been used to effectively control Hypogastrura in mushroom cultures (Hamilton 1976), however, with improved sterilisation techniques Collembola are no longer regarded as important pests of mushrooms (Clift 1983).

CHAPTER 2

GENERAL MATERIALS AND METHODS

(i) Collection techniques

(a) Suction sampling

The extraction of microarthropods from pasture by suction sampling has been previously discussed by Johnson et al (1957), Dietrick (1966), Wallace (1972) and Henderson and Whittaker (1977). In this study the technique was used mainly for the collection of Collembola and their acarine predators from pastures, field crops and occasionally from grasses (eg. along roadsides) and lawns. A portable back-pack suction machine adapted from a STIHL(R) SG 17 mist blower was used. The adapted sampling unit consisted of a two-stroke petrol engine with a flexible inlet hose 2.5 m long and 12 cm in diameter, onto the end of which was attached a handle enabling the hose to be maneuvered. A replaceable orlon collection bag was attached to the end of the hose using three thick rubber bands. Collections were made by dragging the end of the inlet hose over an area of 3-4 m^2 in each pasture sampled. After each collection the orlon bag was removed and replaced with another bag. The bag with its sampled contents was individually placed in an 8x16 cm plastic screw cap jar. The contents were preserved by placing jars in coolite containers with freezer blocks and returned to the laboratory for examination.

The suction method enabled collection of large numbers of epigaeic and hemiedaphic Collembola and Acarina. Johnson et al (op. cit.) report extraction rates exceeding 90% for these arthropods from grassland and herbage under optimum conditions. Sampling wet pasture was avoided where possible because of the reduction in collection efficiency (Henderson and Whittaker op. cit.).

(b) Examination of suction samples

In the laboratory, samples were stored at 4-8°C and examined within three days with most of the fauna still alive. The contents of each jar were first examined in a large plastic tray and a representative sample of the collembolan species and any possible mite predator was collected using an aspirator (Pooter). The contents of the tray were then tipped into a 10 cm diameter petri dish, flooded with 90% alcohol and further examined under a dissecting microscope.

(c) Core sampling (pasture)

This technique was used for monthly population monitoring of surface-active Collembola and predatory Acarina in sample plots selected in S. viridis infested pastures at Moriarty, Elliott Research Station and Flowerdale in north-west Tasmania (a full description of these sites is detailed in Chapter 4). The sampling method employed was similar to that used by Wallace (1956, 1967). A metal cylinder (diameter 10 cm, height 12 cm) with a loose-fitting lid, was hammered ca 5 cm into the ground. The lid was removed, the core quickly inverted and knocked several times against the sides of a 21.5 cm diameter plastic funnel, below which there was a glass tube (diameter 2.5 cm, height 10 cm) containing ca 15 ml of

90% alcohol in which Collembola and Acarina were collected. The funnel was fitted with a fly wire grid cemented to the narrow entrance of the funnel, to ensure that large soil particles and other debris did not enter the collection tubes. Following each sample, the core of soil and pasture was removed from the sample cylinder and replaced in the ground. The collection tube was removed, numbered and stoppered by means of a pres-on cap and replaced by another tube for each sample point determined using a table of random numbers. Two workers were used for this procedure, with one selecting and removing the cores from the pasture and the other transferring the microarthropods into the sample tubes, the sample time was approximately 45 minutes per 30 core samples, depending on the state of the pasture. The time varied according to the condition of the soil, with a hard soil during summer requiring more time than moist soil in winter.

Examination of pasture cores after removal of Collembola and Acarina showed that few individuals were left behind, although some specimens occasionally stuck to the sides of the core on the instances that the pasture was damp following rain. As discussed by Wallace (1956) the method would not be suitable for very dry and sandy soils owing to the difficulty in removing an intact sample. Excessive amounts of soil and associated debris would also pass through the grid into the sample tube when cores were inverted. The technique was satisfactory for the Kransnozem soils sampled in north-west Tasmania where there is an acceptable cover of pasture even in summer months.

After collection the preserved specimens were returned to the laboratory for identification and counting.

(d) Examination of core samples

On return to the laboratory, the contents of each specimen tube (as collected in the field) were emptied separately into a petri dish and examined under a dissecting microscope. Depending on the time of year, it was found that up to 12 different species of Collembola could be present in a core sample. Each separate species of Collembola and predatory Acarina was identified counted, recorded then removed from the petri dish by means of a 'section lifter' and placed in a glass screw cap phial (15 x 55 mm) containing 90% alcohol, there being one phial for each plot for each species for each sample date.

(e) Evaluation of core sample method (estimation of optimum core sample number)

The results of monthly counts of S. viridis for the first 18 months of sampling at Moriarty, Elliott Research Station and Flowerdale were used to estimate optimum sample numbers by calculating the standard errors of each sample as follows:-

$$S\bar{x} = \frac{\sqrt{\frac{s^2}{n}}}{\bar{x}} \times 100$$

$S\bar{x}$ = standard error (expressed as a percentage of the mean)
s^2 = variance
n = number of samples taken
$\bar{x}$ = sample mean

Tables 2.1, 2.2 and 2.3 give the values for Sx calculated for 10,20 30 and 40 core samples per plot at Moriarty and Flowerdale and 10, 20 and 30 core samples at Elliott. No figure is shown for sample numbers 8 to 10 for Moriarty and Elliott and 8 to 9 for Flowerdale owing to the seasonally low summer populations of S. viridis. The results show that the value for Sx was usually lower for Elliott followed by Flowerdale and Moriarty. With 30 core samples, mean Sx values between ca as 12 and 15% were obtained. Although standard error values could be reduced up to 3% by increasing the sample number to 40, it was considered that the extra time and labour involved in attaining the increased accuracy was not justified when a sample number of 30 provided a suitable indication of population fluctuations for the purposes of the study.

(f) Core sampling (soil)

This technique was used for the sampling and population monitoring of euedaphic Collembola in field crops. Soil samples were collected in 5cm diameter PVC tubes hammered to a depth of 5 or 10 cm. Soil cores were removed, placed separately in small labelled plastic bags and returned to the laboratory. The soil cores were then placed separately in 12.5 cm diameter Tullgren funnels and extracted for 3-5 days using a 25 W incandescent light source (distance from light source to grid was 25 cm). The extracted Collembola were collected in 90% alcohol. Specimens from each sample were then examined under a dissecting microscope for sorting, identification and counting.

(g) Other collection methods

Litter sampling was used on a few occasions for collecting Collembola from home gardens. Collected litter was placed in labelled plastic bags and returned to the laboratory. Samples were then extracted in large 30 cm diameter Berlese funnels for 5-7 days using a 60 W incandescent light source (distance from light source to grid was ca 27 cm).

The other collection source was from the specimens brought to the Entomology Section of the Tasmanian Department of Primary Industry by field officers or members of the public during routine enquiries. Records of previous enquiries dated back to 1953 and some specimens had been retained and deposited in the museum collection at New Town Research Laboratories.

Table 2.1 Standard errors ($S\bar{x}$) (expressed as a percentage of the mean) for S. viridis population counts at Moriarty 1.

Sample no.	Sample date	Std. error for 10 samples	Mean no. S. viridis per sample	Std. error for 20 samples	Mean no. S. viridis per sample	Std. error for 30 samples	Mean no. S. viridis per sample	Std. error for 40 samples	Mean no. S. viridis per sample
1	25.5.76	32.6	2.3	-	-	-	-	-	-
2	01.7.76	19.9	2.7	31.8	4.9	24.0	4.6	-	-
3	09.8.76	42.2	2.4	24.4	2.7	17.8	3.4	16.0	3.2
4	13.9.76	19.1	32.1	14.6	30.6	16.0	30.2	13.1	30.2
5	11.10.76	12.1	119.6	9.6	114.8	13.6	123.8	10.5	126.1
6	09.11.76	35.3	42.8	18.7	50.1	20.0	62.2	15.8	62.7
7	06.12.76	28.8	8.1	18.6	8.4	16.2	8.3	12.6	8.6
11	13.4.77	20.7	3.4	14.3	3.7	12.0	3.5	-	-
12	24.5.77	16.6	4.6	12.4	5.2	11.9	6.7	-	-
13	27.6.77	18.2	3.5	23.2	4.8	17.9	4.5	-	-
14	25.7.77	21.9	5.7	13.4	7.2	9.9	7.3	-	-
15	25.8.77	61.6	16.7	45.1	11.4	32.3	10.8	-	-
16	15.9.77	10.5	15.9	7.5	15.5	7.8	15.4	-	-
17	17.10.77	19.2	96.8	17.3	106.6	14.2	97.8	-	-
18	01.11.77	0.9	15.7	23.6	36.4	16.8	37.4	-	-
Mean $S\bar{x}$		25.9		18.3		15.4		13.6	

Table 2.2 Standard errors ($S\bar{x}$) (expressed as a percentage of the mean) for S. viridis population counts at Elliott.

Sample no.	Sample date	Std. error for 10 samples	Mean no. S. viridis per sample	Std. error for 20 samples	Mean no. S. viridis per sample	Std. error for 30 samples	Mean no. S. viridis per sample
1	25.5.76	30.9	7.70	-	-	-	-
2	01.7.76	15.4	28.10	13.5	25.40	10.5	24.83
3	09.8.76	13.1	18.60	9.5	19.60	6.9	19.40
4	14.9.76	13.6	12.50	9.4	12.35	6.4	12.73
5	11.10.76	4.6	51.80	7.3	50.50	6.0	49.07
6	09.11.76	18.5	55.80	9.2	58.75	7.7	56.87
7	07.12.76	19.0	25.40	12.4	23.80	9.5	22.43
11	14.4.77	22.5	62.30	15.9	64.55	2.4	68.80
12	24.5.77	13.5	20.50	11.5	22.50	9.8	20.43
13	28.6.77	23.0	32.50	15.3	41.80	13.0	35.67
14	25.7.77	16.1	58.30	11.1	66.80	9.3	67.77
15	25.8.77	11.5	28.70	10.7	26.05	8.5	26.13
16	14.9.77	19.5	17.80	11.1	20.9	8.5	20.83
17	17.10.77	13.9	44.70	12.4	34.95	9.9	39.17
18	22.11.77	19.3	12.10	10.4	13.40	10.1	11.37
Mean $S\bar{x}$		16.9		13.3		11.9	

Table 2.3 Standard errors ($S\bar{x}$) (expressed as a percentage of the mean) for S. viridis population counts at Flowerdale.

Sample no.	Sample date	Std. error for 10 samples	Mean no. S. viridis per sample	Std. error for 20 samples	Mean no. S. viridis per sample	Std. error for 30 samples	Mean no. S. viridis per sample	Std. error for 40 samples	Mean no. S. viridis per sample
1	24.5.76	27.7	8.8	-	-	-	-	-	-
2	02.7.76	18.0	9.8	13.7	0.8	15.0	11.7	-	-
3	10.8.76	25.1	5.1	23.7	10.7	16.1	12. 4	-	-
4	15.9.76	25.2	9.1	14.5	10.9	11.1	10.3	10.3	11.3
5	12.10.76	13.8	57.2	9.3	56.3	7.7	58.0	7.3	55.7
6	10.11.76	18.7	79.1	12.8	72.4	9.2	78.2	8.3	79.5
7	06.12.76	29.8	27.0	16.6	27.8	11.7	28.9	9.6	30.7
10	08.03.77	26.1	2.2	22.3	1.8	23.4	1.4	-	-
11	13.4.77	21.3	20.1	12.1	21.9	8.6	23.0	-	-
12	25.5.77	13.4	19.2	10.6	19.9	10.8	20.3	-	-
13	28.6.77	19.6	31.1	15.6	28.1	12.3	29.2	-	-
14	25.7.77	11.3	17.0	12.0	13.8	12.5	12.0	-	-
15	25.8.77	17.5	13.2	11.7	12.6	10.9	13.7	-	-
16	14.9.77	14.3	25.0	10.6	24.2	10.3	25.9	-	-
17	18.10.77	17.8	22.2	13.5	24.7	19.2	1.8	-	-
18	21.11.77	17.3	104.8	14.3	162.7	10.8	166.4	-	-
Mean $S\bar{x}$		21.4		13.3		11.9		8.9	

(ii) Storage and identification of Collembola and predatory Acarina
Voucher specimens of Collembola and predatory Acarina collected during surveys and from monitored plots were labelled and stored in 90% alcohol in 15 x 55 mm screw-top phials and deposited in the museum collection at New Town Research Laboratories.

A full description of the identification methods used for the Collembola, together with a key to the identification of the species collected in the Tasmanian culture steppe during this study is presented in Chapter 13. Identification of mites from the families Bdellidae and Spinidellidae was determined using keys by Atyeo (1963) and Wallace and Mahon (1972, 1976). Initially, in order to be certain that the keys were being correctly interpreted, specimens were sent to Dr M. M. H. Wallace (CSIRO, Canberra) for confirmation. Identifications of Anystidae were determined using the key of Oudemans (1936) and more recently Meyer and Ueckermann (1987), as well as by personal communication with Wallace. Voucher specimens of Parasitididae were forwarded to Dr D. C. Lee (South Australian Museum, Adelaide) for identification. Subsequent identifications were made using these specimens and the key of Bhattacharyya (1963) used by Lee.

(iii) Clearing and mounting techniques for Collembola and Acarina
Specimens were cleared by placing them in covered cavity blocks (40 mm X 3 mm) containing either Kono's medium or Lacto-phenol solution and holding them at laboratory temperature (ca 21°C). Clearing time at this temperature varied considerably depending on the degree of pigmentation. Most cleared within 24 hours but some heavily pigmented specimens such as hypogastrurid Collembola required as long as 72 hours; leaving specimens for extended periods of time in these solutions was usually avoided because of the risk of cuticle disintegration (Singer 1967). If rapid clearing of heavily pigmented specimens was required they were placed in a watch glass of clearing fluid, slowly heated to below boiling point then allowed to cool. This enabled clearing within a few minutes.

After clearing, specimens were mounted separately on slides in modified Berlese medium, oven dried and then ringed with euparal. Slides were labelled and deposited in the museum collection at New Town Research Laboratories.
Clearing and mounting media recipes are listed as follows:-

Clearing media

Kono's preparatory mixture (Jeppson et al 1975)
100 g chloral hydrate
10 g glycerine
50 ml water
1 ml conc. hydrochloric acid

Lacto-phenol solution (Singer 1967)
20 ml Lactic acid (85%)
2 g chloral hydrate
20 ml phenol (molten)

Mounting media

Modified Berlese fluid (Swan 1936)

60 g chloral hydrate
20 ml distilled water
15 g gum arabic
10 g glucose syrup
5 ml glacial acetic acid

(iv) Photography

(a) Scanning electron microscopy

This technique was utilised for photographing Hypogastruridae and Onychiuridae to illustrate the keys presented in Chapter 13. Specimens were removed from storage in 90% alcohol and transferred to absolute alcohol for at least 1 hour. They were cleaned in a Unisonics Ultrasonic Cleaner (Model FX10). The trough was filled with a few cm of water and tubed alcohol specimens were immersed for ca 5-10 seconds. Specimens were then dried using the critical point method in a Balzers Union Critical Point Drier (Model FL-9496) and gold coated in a Dynavac Sputter Coater (Model SC-150). Examination and photography was carried out using a Cambridge Stereoscan 100 electron microscope.

(b) Colour photography

Colour photography was mainly carried out to illustrate the key to Collembola presented in Chapter 13. The equipment consisted of a Leica MDa (35 mm) camera and a Leitz aristophot photomacrographic outfit with bellows unit using Leitz photar lenses (1 : 2.8/50), 1 : 2.5/25). Exposures were made using Braun synchronised twin head electonic flashes (at 45°). Exposures were based on readings obtained on a Zelox Flashmeter M-3 at the specimen position. Preserved specimens (including mites) were photographed immersed in 90% alcohol in a 100 mm diameter glass petri dish. Photography of a few live specimens was also carried out by placing them in an empty (covered) 100 mm glass petri dish and anaesthetizing them with carbon dioxide. The specimens were photographed as soon as they had assumed a normal position just after the affects of the CO_2 had worn off but before they became fully active.

Other photographs were taken with an Asahi Pentax K 1000 (35 mm) using a 50 mm close-up lens.

(v) Meteorological records

All meteorological data used in this thesis were obtained through the Commonwealth Bureau of Meteorology, Hobart.

CHAPTER 3

A RE-EXAMINATION OF THE DISTRIBUTION OF THE PASTURE SNOUT MITE *BDELLODES LAPIDARIA* (KRAMER) (ACARI:BDELLIDAE) AND THE LUCERNE FLEA, *SMINTHURUS VIRIDIS* (L.) (COLLEMBOLA:SMINTHURIDAE) IN TASMANIAN PASTURES

INTRODUCTION

The predatory mite, Bdellodes lapidaria (Kramer) was introduced into Tasmania from Western Australia in 1933 (Currie 1934) in an attempt to control populations of the lucerne flea, Sminthurus viridis (L.), however, shortly after 1933 it was found established in areas where it had not been released (Evans 1939), indicating that it had been accidentally introduced much earlier.

Detailed surveys mainly during 1962 established the distribution of S. viridis and B. lapidaria in Australia, assessed the factors limiting the distribution of these species and also showed that the occurrence of B. lapidaria was widespread in Tasmania (Wallace and Mahon 1971).

The north-west coast of Tasmania is the major dairying area of the State and pastures are regularly sprayed in autumn and spring for the control of S. viridis. Because B. lapidaria is considered to play an important role in determining S. viridis population size (Wallace 1967), another more detailed Tasmanian survey was begun after population studies on the north-west coast at Elliott, Moriarty and Flowerdale during 1976 (Chapter 4) suggested that B. lapidaria might be limited in its ability to control populations of S. viridis in this area.

This Chapter presents the results of this latest survey and enables (i) a more thorough assessment of the distribution of B. lapidaria in Tasmania in relation to that of S. viridis and (ii) a discussion of the possible factors which limit the distribution of both species in Tasmania and therefore affect the importance of B. lapidaria as a predator of S. viridis.

MATERIALS AND METHODS

(i) Collection and examination of samples

Samples were collected using the suction technique and examined according to the methods outlined in Chapter 2. For this survey results from the examination of 280 samples taken in pasture from 1976 to 1983 were used. Table 3.1 details the sample periods. Nearly 60% of samples were taken in autumn and spring months as populations of B. lapidaria, S. viridis and many other collembolan species were known to reach their maximum levels in Tasmanian pastures during these periods. This knowledge was based on previous Tasmanian work on S. viridis by Evans (1937) and population monitoring carried out during this study (see Chapters 4 and 8).

Most of the samples were taken from improved pastures of perennial ryegrass (Lolium perenne), white clover (Trifolium repens), subterranean clover (Trifolium subterraneum) and cocksfoot (Dactylis glomerata), while a minority were taken from semi-improved pastures where Poa spp. Agrostis spp., Cynosurus spp. and Holcus lanatus predominated. Pastures were sampled in the east, north-east, south-east, midlands and central

highland areas, north, north-west and the only significant area of improved pasture that occurs in the remaining western areas, ca 567 ha at Granville Harbour on the west coast.

Table 3.1 Pasture survey sample periods for S. viridis and B. lapidaria (1976-1984).

	Season				
	Summer (Dec-Feb)	Autumn (Mar-May)	Winter (June-Aug)	Spring (Sept-Nov)	Totals
Total per season	57	92	57	74	280
%	20.4	32.8	20.4	26.4	100

(ii) Distribution parameters

Distributions were examined in relation to the following parameters:

(a) Climatic zones of Walter and Lieth (1967) and wet and dry pasture ecotypes (McQuillan and Ireson (1982)

The zones are designated as mediterranean with winter rains (Type IV); warm temperature and humid (Type V) and typical of mountain areas (Type X) (Figs 3. 1 and 3.2). Although the zones provide a useful division of the State into different climatic areas, they only define the differing climatic areas of Tasmania on a broad basis. In particular there are no areas of the State with a typically Mediterranean climate as defined by the Type IV zone. Such areas have their maximum rainfall in winter with a long summer drought season. North-west and some north-east localities do receive their maximum rainfall in winter, however, they are rarely subjected to a long summer drought. Also, in many central and eastern areas classified as Type IV, rainfall is evenly distributed throughout the year with no winter maximum. Further, the large Type V area which involves the majority of the Western half of the State (mean annual rainfall > 1200 mm) receives considerably more rain than the drier and warmer Type V area designated for eastern and south-eastern parts of the State. It is therefore more useful to consider these zones in combination with the 800 and 1200 mm annual isohyets, hence the inclusion of both parameters in Figs 3.1 and 3.2.

These isohyets not only delineate the wet and dry areas of Tasmania, they also reflect the two major Tasmanian pastoral enterprises of dairying and beef production in high annual rainfall areas (> 800mm) and sheep and beef production in low annual rainfall areas (<800 mm) (McQuillan and Ireson 1982). The main features of the two pastoral ecotypes are summarised in Table 3.2. Survey results were expressed into contingency tables and analysed using the log-linear model technique of generalised linear models (McCullagh and Nelder 1983) to determine possible

preferences of S. viridis or B. lapidaria for the wet or dry pasture ecotype.

Table 3.2 General features of the two pastoral ecotypes in Tasmania (after McQuillan and Ireson 1982).

Attribute	Low Rainfall	High Rainfall
Annual rainfall	500 - 800 mm	800 - 1 600 mm
Main area	Midlands, south-east	North-west
Rainfall distribution	+ Uniform	Winter maximum
Rainfall variability	High	Lower
Main soils	Prairie soils, Podsols	Krasnozems, Podsols
Common sown species	Lolium perenne, Trifolium subterraneum	Lolium perenne, Dactylis glomerata, Trifolium repens
Original vegetation	Sclerophyll forest	Rainforest
Main grazing animals	Sheep	Dairy cattle

(b) 225 mm December-March isohyet
This isohyet (Figs 3.3, 3.4 and 3.5) was used by Wallace and Mahon (1971) to define the eastern limits of the S. viridis distribution in New South Wales and Victoria and that of B. lapidaria in Victoria and Tasmania.

The stippled area on the maps in Figs 3.1-3.4 and 3.5 indicates the approximate area of sown pasture (900,000 ha).

(c) Rainfall - evaporation isopleths
The rainfall - evaporation ratio is useful as a single factor index to moisture conditions at the soil surface and was used by Davidson (1934) who provided maps to forecast the probable limits to the distribution of S. viridis in Australia.

Comparatively few stations take direct evaporation readings and in Tasmania such data was obtainable from 21 stations. Evaporation figures for a further 29 stations were extrapolated by calculating saturation deficit.

Evaporation is related to saturation deficit by the equation:

$$E = K \times s.d.$$

Where K is a constant

E = evaporation (mm)

s.d. = saturation deficit (h. pa)

Saturation deficit is a function of temperature and relative humidity and was calculated as follows:

$$\% \text{ R.H.} = \frac{Ew}{Es} \times 100$$

Where R.H. = mean relative humidity

Es = total vapour pressure at the ambient temperature

Ew = actual vapour pressure at the ambient temperature

and s.d. = Es - Ew

Ew is given by the equation:

$$Ew = 1013.2e^{(T\ (13.3185 - T\ (1.976 + T\ (0.6445 + T\ (0.1299))))}$$

and T is given by the equation:

$$T = \frac{(\text{mean temp.} - 100)}{(\text{mean temp.} + 273.16)}$$

Once Ew and R.H. are calculated the value for Es and therefore s.d. can be obtained.

Prescott (1934) gave a value for K of 259 when calculating K from imperial units (evaporation in inches and s.d. in inches of mercury). When calculating the constant for values of evaporation and s.d. in metre units, the constant approximates 16. This value was based on the mean of annual figures of evaporation and s.d. for stations around Australia. For this study values of K were determined for the 21 stations in Tasmania where evaporation figures were available. In this way a mean K value was determined for each month of the year for the different regions of the State. The R/E ratio was then calculated for each month for 50 of the States weather stations. The months considered favourable by Davidson (1934) for population increases of S. viridis were those in which the R/E ration was not less than approximately 1 and the range of mean monthly temperatures was 11.1 - 15.6°C.

(d) Isotherms

The distribution of both S. viridis and B. lapidaria in Tasmania was examined in relation to a range of Isotherms, including those for each month of the year.

(e) Soil type

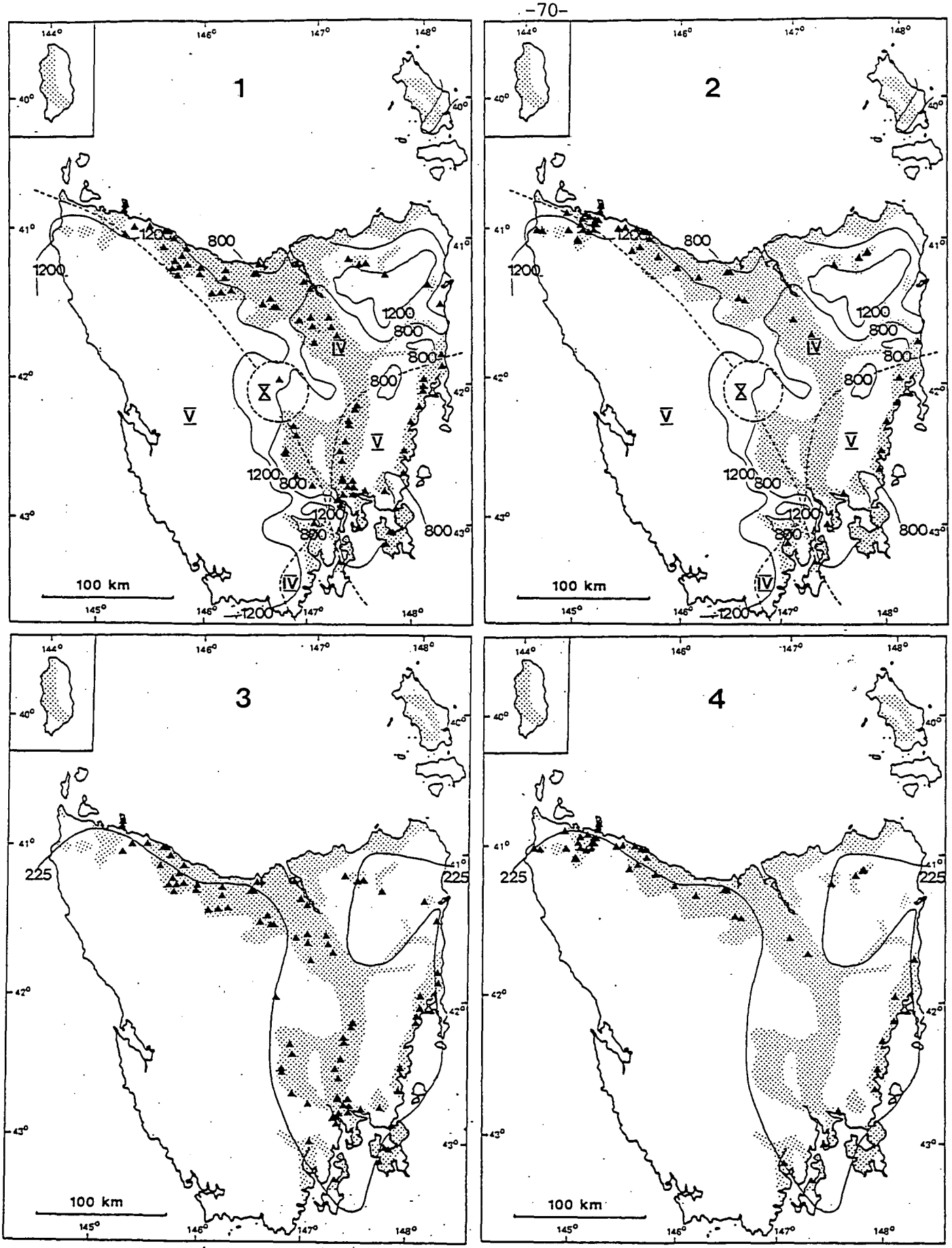
The distribution of S. viridis in pasture was examined in relation to this parameter. Soil type was discussed by Maclagan (1932a) and Davidson (1934) as an important factor in affecting oviposition by S. viridis.

RESULTS

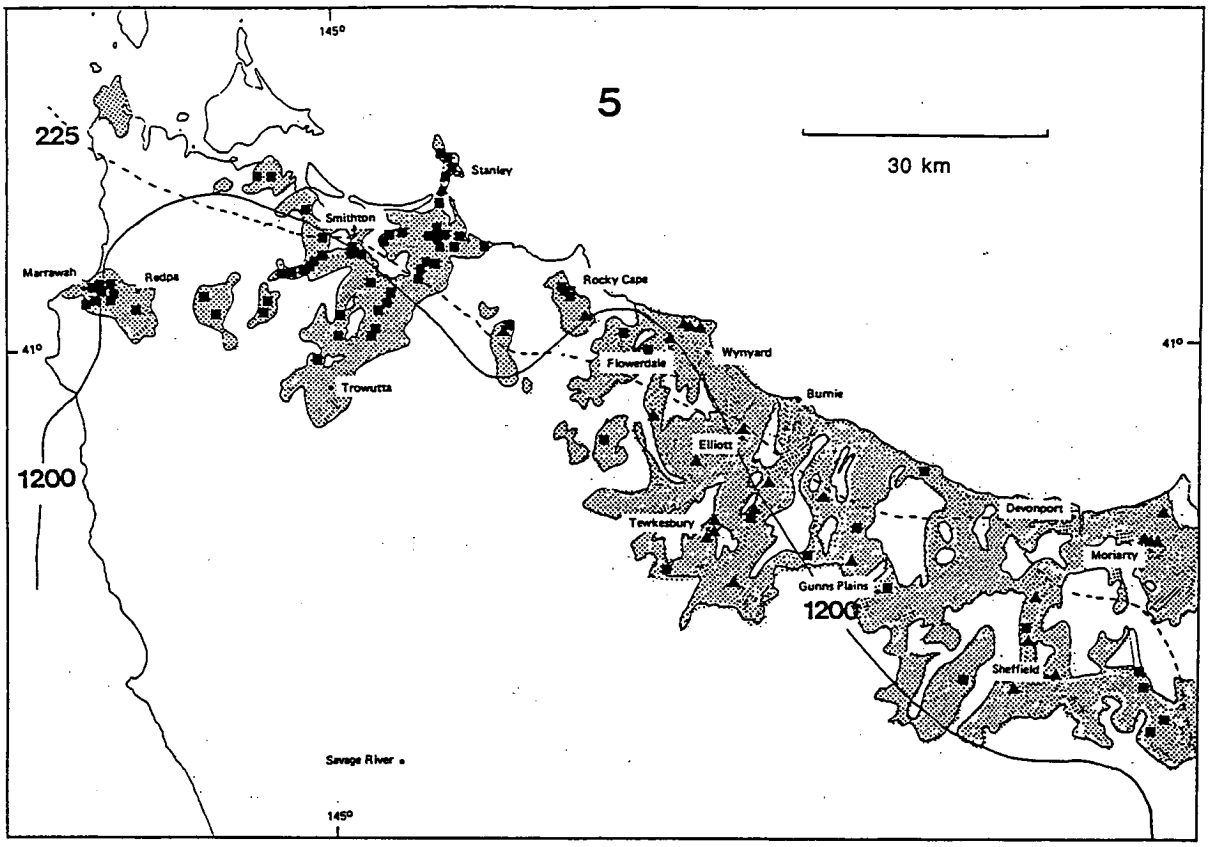
The Statewide distribution data for B. lapidaria and S. viridis are shown in relation to Figs 3.1-3.4 respectively while Fig. 3.5 shows key localities sampled for B. lapidaria and its distribution in north-west Tasmania. Fig. 3.6 shows the isotherms for the warmest month of the year (February) and Fig. 3.7 the isotherms for the coolest month (July).

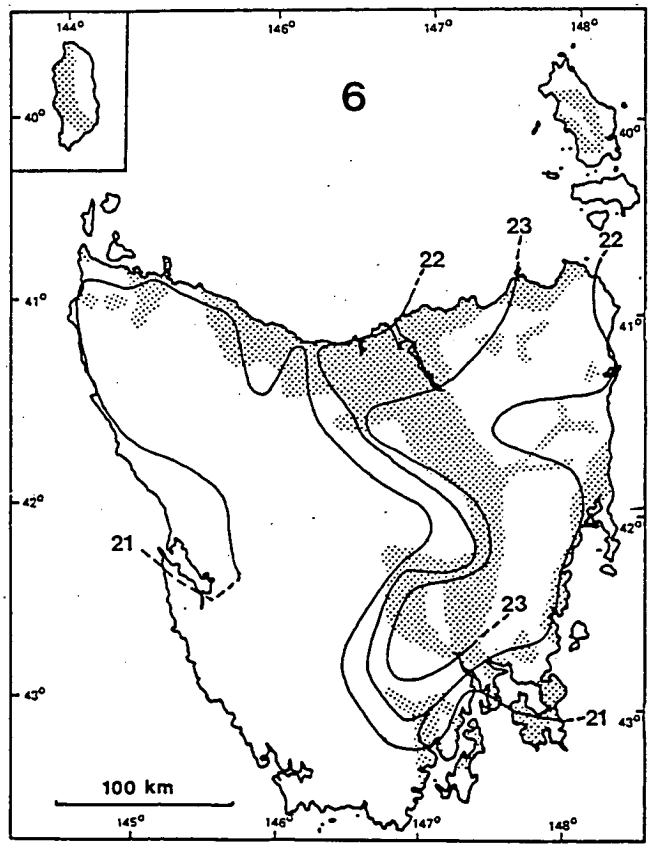
Figs 3.1-3.2 Distribution of B. lapidaria (1) and S. viridis (2) in Tasmania in relation to the climatic zones of Walter and Lieth (1967) and the 800 and 1200 mm annual isohyets.

Figs 3.3-3.4 Distribution of B. lapidaria (3) and S. viridis (4) in Tasmania in relation to the 225 mm December-March isohyet. Stippling on maps is equivalent to the approximate area of sown pasture (ca 900,000 ha).


1
2
3
4
144°
146°
147°
148°
40°
41°
42°
43°
145°
1200
800
225
IV
V
100 km

Figs 3.5-3.7 Distribution of B. lapidaria (5) in pastures in north-west Tasmania in relation to the 1200 mm annual isohyet and the 225 mm December-March isohyet (■ indicates sample sites where B. lapidaria was absent, ▲ where B. lapidaria was present); isotherms for February (Tasmania) (6); isotherms for July (Tasmania) (7).


5
30 km
225
1200
1200
Stanley
Smithton
Marrawah
Redpa
Rocky Cape
Wynyard
Flowerdale
Trowutta
Burnie
Elliott
Tewkesbury
Devonport
Moriarty
Gunns Plains
Sheffield
Savage River
145°
41°


6
144°
146°
147°
148°
40°
41°
42°
43°
23
22
22
21
23
21
100 km
145°

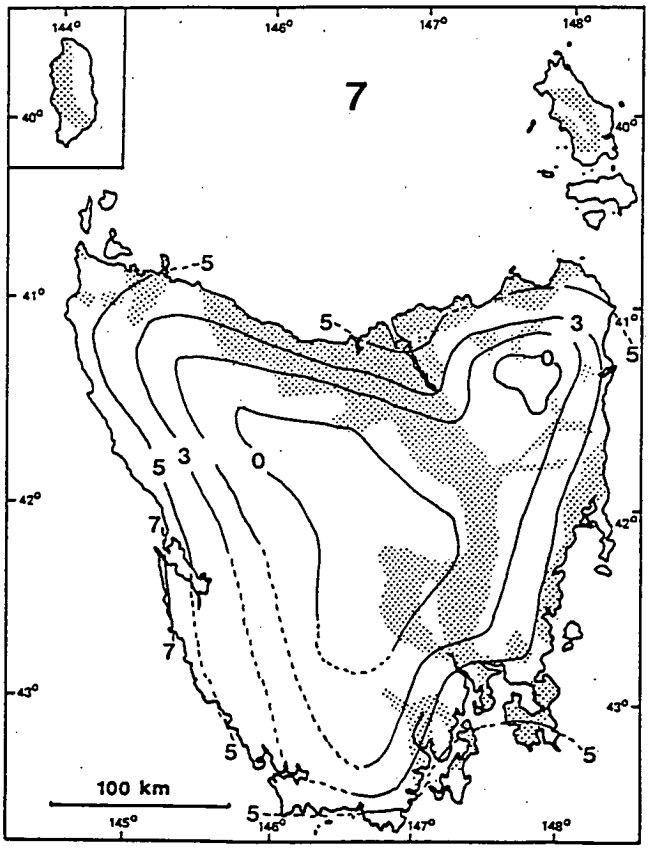

7
144°
146°
147°
148°
40°
41°
42°
43°
5
5
3
0
5
3
0
7
7
5
5
5
100 km
145°

Table 3.3 shows the incidence of these species in samples taken at localities around the 1200 mm isohyet (Type IV-V climate) in the far north-west to the west of Rocky Cape compared to their incidence in samples from the sub-alpine region (Type X climate, mean annual rainfall ca 850 mm) and drier midland-eastern areas (Type IV-V climate, mean annual rainfall <800 mm). Table 3.4 compares the incidence of S. viridis and B. lapidaria in wet and dry pastures. Table 3.5 provides a key to the statewide distribution and activity of S. viridis as determined through surveys and in relation to the R/E ratio and temperature parameters and the presence of Krasnozem soils, a soil type which was usually found to be associated with high S. viridis populations. Fig. 3.8 shows the mean density of S. viridis populations sampled monthly over a 4 year period from May 1976 to April 1980 at Elliott, Moriarty and Flowerdale in the north-west (see Chapter 4); seasonal peaks are recorded in winter (June) and Spring (October).

DISCUSSION

(i) Distribution of B. lapidaria

The consistent absence of B. lapidaria from the far north-west region in the current surveys suggests that some factor is affecting the establishment of permanent populations in this region where S. viridis is a pest. Wallace and Mahon (1971) examined the Australian distribution of B. lapidaria in relation to rainfall isohyets and stated that the wet limits in eastern Victoria and eastern and western Tasmania are approximated by the 225 mm isohyet for the December-March period, while the inland or dry limits to its distribution on the mainland approximate the 260 mm isohyet for the May-October period. They also referred to temperature and related the absence of B. lapidaria in coastal areas of Western Australia, within the 260 mm isohyet limit, to a mean maximum temperature for the coolest month (usually July) exceeding around 17.5°C. Additionally, they concluded that B. lapidaria was widespread in Tasmania with its range including almost all the area occupied by S. viridis.

The current survey demonstrates that in north-west Tasmania the range of B. lapidaria extends into wetter areas beyond the 225 mm isohyet limit of Wallace and Mahon (1971) (Figs 3.3, 3.5) at least as far as Tewkesbury (mean annual rainfall ca 1500 mm) where the December-March rainfall is 312 mm. The absence of B. lapidaria from localities within the 312 mm isohyet to the west of Rocky Cape suggests that different factors limit the distribution of B. lapidaria in the far north-west.

The far north-west, where B. lapidaria was absent from pastures during surveys, experiences a wet, mild climate and is climatically unique when compared to the rest of the State. Apart from the high annual rainfall (ca 1200 mm), which predominates in winter, there is less seasonal fluctuation in temperature. Temperatures range from a maximum of ca 20-22°C in February (Fig. 3.6) to a minimum of ca 4-6°C in July (Fig. 3.7) which is also the wettest month for this region.

Table 3.3 Incidence of *B. lapidaria* and *S. viridis* in samples taken west of Rocky Cape in north-west Tasmania compared to sub-alpine, midland and eastern areas.

Species	Number of samples containing species		
	West of Rocky Cape % n = 61	Other areas % n = 74	Significance level for difference
B. lapidaria	3.3	62.2	$P < 0.01$
S. viridis	59.0	12.2	$P < 0.01$

Table 3.4 Frequency of occurrence and seasonality of *S. viridis* and *B. lapidaria* in low and high rainfall pastures based on analysis of survey data.

Species	Season	% High rainfall	% Low rainfall	% Total
S. viridis	Spring	41.8	5.3	32.4
	Summer	5.9	4.4	7.0
	Autumn	37.5	5.0	29.4
	Winter	71.4	20.9	33.3
	Totals	35.4	11.4	26.4
	X^1_2	(high/low) = 21.3**		
	X^1_3	(seasonal) = 17.8**		
B. lapidaria	Spring	25.5	68.4	36.5
	Summer	41.2	34.8	38.6
	Autumn	25.0	30.0	26.1
	Winter	7.1	51.2	40.4
	Totals	26.9	46.7	34.3
	X^1_2	(high/low) = 11.3**		
	X^1_3	(seasonal) = 4.04 n.s.		

Significance Level: X^1_2, 5% = 3.84 X^1_3, 5% = 7.01
X^1_2, 1% = 6.63 X^1_3, 1% = 11.3

KEY TO TABLE 3.5

S. viridis

H = Pest status high (frequently causing severe damage to clover)

R = Recorded at sites in this locality but pest status in pastures not high (may cause occasional damage to clover)

NR = Samples taken from pastures in this locality but species not recorded

? = Pastures present in the vicinity of this locality but sites not sampled

PA = No significant area of improved pasture in the vicinity of this locality

Soil type

K = Krasnozem soils common in these localities

O = Soil types other than Krasnozems predominating

Monthly weather data

/ = R/E > 1

++ = T > 15.6°C

+ = 11.1°C < T < 15.6°C

- = T < 11.1°C

x = T ≃ 11.1°C

Table 3.5 Statewide distribution and activity of *S. viridis* in relation to the R/E ratio, temperature parameters and the presence of Krasnozem soils.

Locality	*S. viridis*	Soil type	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
North-West														
Burnie	H	K	++	++	++	/+	/x	/-	/-	/-	/x	/+	+	+
Devonport	H	K	++	++	+	/+	/-	/-	/-	/-	/-	x	+	+
Devonport East	H	K	++	++	+	/+	/x	/-	/-	/-	-	x	+	+
Elliott	H	K	+	++	+	/+	/x	/-	/-	/-	/-	/x	+	+
Erriba	NR	K	+	+	/+	/-	/-	/-	/-	/-	/-	/-	/-	/x
Forthside	H	K	++	++	+	/+	/-	/-	/-	/-	/-	x	+	+
Gunns Plains	H	K	++	++	+	/x	/-	/-	/-	/-	/-	x	+	+
Marrawah	H	K	++	++	/+	/+	/x	/-	/-	/-	/-	/x	/+	+
Preolenna	H	K	+	++	+	/+	/-	/-	/-	/-	/-	/x	/x	+
Quoiba	R	K	++	++	+	/+	/-	/-	/-	/-	/-	x	+	+
Redpa	H	K	+	+	+	/+	/x	/-	/-	/-	/-	/x	+	+
Savage River	PA	O	+	+	/+	/x	/-	/-	/-	/-	/-	/-	/x	/+
Sheffield	H	K	+	++	+	/x	/-	/-	/-	/-	/-	-	+	+
Smithton P.O.	H	K	++	++	+	/+	/x	/-	/-	/-	/-	x	+	+
Stanley	H	K	++	++	++	/+	/x	/-	/-	/-	/x	/+	+	+
Tewkesbury	NR	K	+	/+	/+	/x	/-	/-	/-	/-	/-	/-	/x	/+
Wynyard West	H	O	++	++	+	/+	/+	/-	/-	/-	/-	x	+	+
North-East														
Eddystone	PA	O	++	++	++	/+	/+	/x	/-	/-	/x	+	+	+
Launceston	R	O	++	++	+	x	/-	/-	/-	/-	-	x	+	+
Mt Barrow	PA	O	-	/x	/-	/-	/-	/-	/-	/-	/-	/-	/-	/-
Scottsdale	H	K	++	++	+	/+	/-	/-	/-	/-	/-	/x	+	+

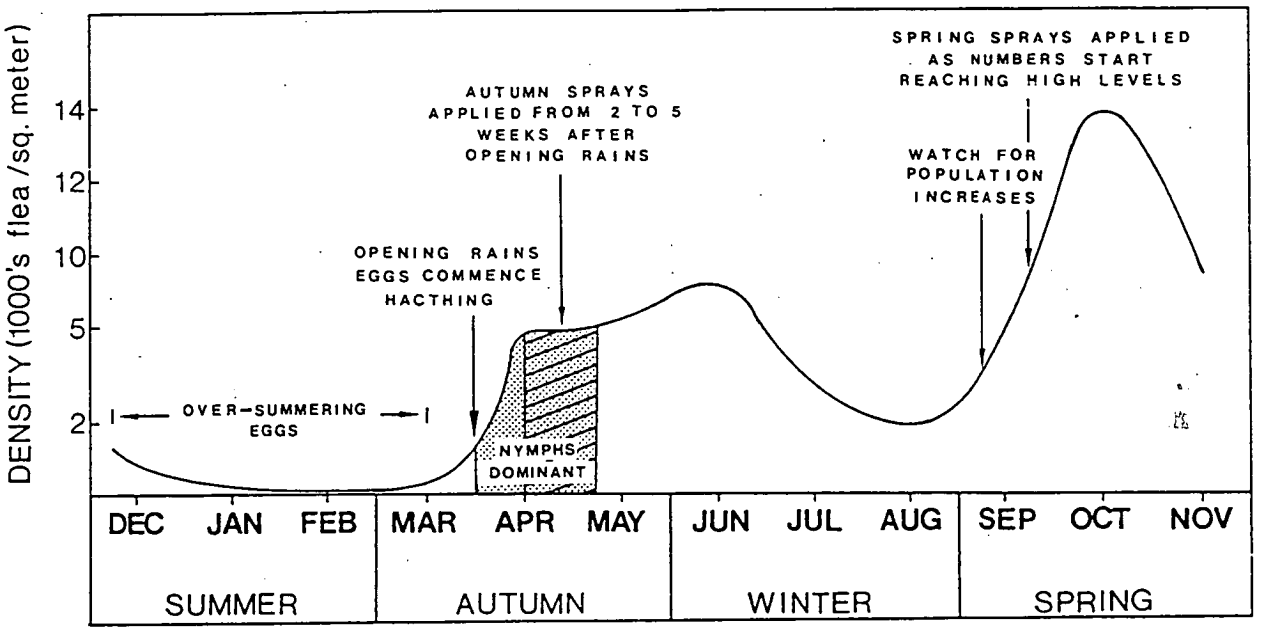
Table 3.5 cont. Statewide distribution and activity of S. viridis in relation to the R/E ratio, temperature parameters and the presence of Krasnozem soils.

Locality	S. viridis	Soil type	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
North														
Cressy	R	O	++	++	+	x	/-	/-	/-	/-	-	x	+	+
Deloraine East	R	K	++	++	+	/+	/-	/-	/-	/-	/-	/x	+	+
Georgetown	?	O	++	++	++	/+	/x	/-	/-	/-	/-	x	+	+
Low Head	R	O	++	++	++	+	/x	/-	/-	/-	/x	+	+	+
Midlands														
Bothwell	NR	O	+	+	+	/x	/-	/-	/-	/-	/-	-	+	+
Bronte	NR	O	+	+	x	/-	/-	/-	/-	/-	/-	/-	/-	+
Bushy Park	NR	O	++	++	+	/+	/-	/-	/-	/-	/-	x	+	+
Campbell Town	NR	O	++	++	++	x	/-	/-	/-	/-	/-	/x	+	+
Oatlands	NR	O	+	+	+	x	/-	/-	/-	/-	-	-	+	+
East														
Bicheno	NR	O	++	++	++	+	/+	/x	-	-	x	+	+	+
Lake Leake	PA	O	+	+	+	/-	/-	/-	/-	/-	/-	-	x	+
Orford	R	O	++	++	++	+	/x	/-	/-	/-	/-	+	+	+
Rossarden	?	O	+	+	+	-	/-	/-	/-	/-	/-	-	x	+
Scamander	NR	O	++	++	/++	+	/+	/-	/-	/-	x	+	+	+
St Helens	?	O	++	++	++	+	/+	/-	/-	/-	x	+	+	+
Swansea	R	O	++	++	+	+	/+	/-	/-	-	x	+	+	+
Central														
Shannon	NR	O	+	+	-	/-	/-	/-	/-	/-	/-	/-	-	-
Lake St Clair	PA	O	+	+	x	/-	/-	/-	/-	/-	/-	/-	/-	/x

Table 3.5 cont. Statewide distribution and activity of *S. viridis* in relation to the R/E ratio, temperature parameters and the presence of Krasnozem soils.

Locality	*S. viridis*	Soil type	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
South														
Geeveston	NR	0	+	+	+	/+	/-	/-	/-	/-	/-	x	+	+
Grove	NR	0	+	+	+	/+	/-	/-	/-	/-	/-	x	+	+
Maydena	PA	0	+	+	/+	/x	/-	/-	/-	/-	/-	/-	/+	/+
Hastings Chalet	PA	0	+	+	/+	/+	/-	/-	/-	/-	/-	/x	/+	/+
South-East														
Cape Bruny	M	0	+	+	/+	/+	/x	/-	/-	/-	/-	/x	/+	/+
Hobart	R	0	++	++	+	+	/x	/-	/-	/-	x	+	+	+
New Norfolk	R	0	++	++	+	/+	/-	/-	/-	/-	x	+	+	+
Tas. Island	PA	0	/+	/+	/+	/+	/+	/-	/-	/-	/-	/-	/x	/+
South-West														
Strathgordon	PA	0	/+	/+	/+	/x	/-	/-	/-	/-	/-	/-	/x	/+
West														
Queenstown	PA	0	/+	/+	/+	/+	/-	/-	/-	/-	/-	/-	/+	/+

Fig 3.8 Mean monthly population estimates of S. viridis over a 4 year period from May 1976 to April 1980 at monitored sites at Moriarty, Elliott Research Station and Flowerdale in north-west Tasmania.


DENSITY (1000's flea /sq. meter)
14
12
10
5
2
SPRING SPRAYS APPLIED AS NUMBERS START REACHING HIGH LEVELS
AUTUMN SPRAYS APPLIED FROM 2 TO 5 WEEKS AFTER OPENING RAINS
WATCH FOR POPULATION INCREASES
OPENING RAINS EGGS COMMENCE HACTHING
OVER-SUMMERING EGGS
NYMPHS DOMINANT
DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
SUMMER
AUTUMN
WINTER
SPRING

By comparison, the midlands and eastern areas are drier (<800 mm per annum) with slightly hotter summers (ca 22-24°C in February) and colder winters (ca 0-2°C in July). Sub-alpine areas are also drier (ca 850 mm per annum) and also experience a wider seasonal temperature fluctuation than the far north-west (ca 18°C in February to ca -4°C in July).

In Tasmania therefore, it appears that B. lapidaria is unsuited to the climatic conditions that prevail in the far north-west. Furthermore, the species showed a significant preference for the drier pasture ecotype (Table 3.4) and is more suited to the conditions that prevail particularly in midland, eastern and sub-alpine areas.

Although the actual mechanisms involved in this limitation are unknown, it is probable that the explanation lies in the affect of the far north-west climate on the ability of B. lapidaria to produce eggs rather than on the eggs themselves. Perhaps soil type and soil pH, which affect the oviposition behaviour of S. viridis (Davidson 1932b; Davidson 1934; Maclagan 1932a), are also playing a role here. Wallace (1971) showed that diapause in eggs of B. lapidaria is obligate and there does not appear to be any substantial difference in behaviour between batches of eggs laid at different times of the year as there is with S. viridis (Wallace 1968). He examined diapause development of B. lapidaria eggs under dry and moist conditions at a range of constant temperatures and found that although there were differences in development rates, temperatures ranging between 1°C and 38°C had no effect on viability.

The results demonstrate a requirement for further biological control attempts by the introduction of mite predators of S. viridis which are potentially better adapted to the climate of north-west Tasmania.

(ii) Distribution of S. viridis

Although the results show that parameters used by Davidson (1934) enable prediction of the distribution limits of S. viridis in Tasmania with reasonable accuracy, he forecast that the cold conditions of mid-winter would severely restrict activity during this period. The results from the surveys and monitored plots (Fig. 3.8) show that this is not so. Populations reached a maximum in June and although this was followed by a steady decrease in activity in association with decreasing winter temperatures, densities of ca 2000/m^2 were recorded in July and August. However, populations at these levels do not exceed economic thresholds (Ireson unpubl. data) and no sprays need be applied. Examination of the distribution of S. viridis in relation to Tables 3.4 and 3.5 shows that populations thrive best in the wet pastures of the north-east and parts of the north-west where the R/E ratio exceeds 1 and temperatures fluctuate between ca 11°C and 15.6°C during April and/or May and again in mid- to late spring when S. viridis populations reach their annual maxima (Fig 3.8). Localities in the far north-west in the vicinity of Stanley, Smithton, Wynyard, Marrawah, Devonport and Burnie and in the north-east

near Scottsdale, which experience the abovementioned conditions during successive months in April and May and for 1 or 2 months in spring, are the areas where the pest status of S. viridis is highest, particularly in pastures sown on Krasnozem soils (pH 5.0-6.0) (Table 3.5). The physical character of this soil is favourable for S. viridis oviposition probably because of its high water-holding capacity. In addition, females oviposit most freely on soils with a pH range of 5.5 - 7.0 (Davidson 1934). Maclagan (1932a) suggested that the effect of soil type on oviposition was exerted through its effect on nutrition of the adult as soil is an important part of the diet, especially during the reproductive phase. In the far north-west, Trowutta (Fig. 3.5) defines the current limits of inland pasture development where S. viridis has established. Table 3.5 shows that weather conditions suitable for the establishment of S. viridis in this district extend well inland (see data for Savage River). Therefore, it would be possible for S. viridis to establish in far north-west pastures to the south of Trowutta if land clearing for agriculture proceeded further inland and other factors such as soil type were not limiting. The R/E data for Tewkesbury (Table 3.5) suggest that prevailing conditions would restrict S. viridis activity in this locality from late autumn through to early spring, but would be suitable from November to April inclusive with the exception of January when the R/E ratio falls below 1. Unlike B. lapidaria, however, S. viridis was not located near Tewkesbury. The use of the R/E ratio to predict the occurrence of S. viridis in summer rainfall areas of eastern Victoria and New South Wales also breaks down (Wallace and Mahon 1971). Wallace (1968) reported that S. viridis at different times of the year laid eggs of different types, one developing and hatching normally and the other undergoing a prolonged incubation period. He showed that the occurrence of diapause eggs in S. viridis is a facultative response to environmental conditions at any particular time of the year, not an obligate response as with B. lapidaria and that S. viridis produces activating eggs when feeding on maturing annual plants. Therefore, as discussed by Wallace and Mahon (1971), a possible reason for the absence of S. viridis from areas of high summer rainfall (in this case Tewkesbury), is that diapause aestivating eggs are not produced because the maturing spring herbage is not available to provide the required stimulus. S. viridis is therefore unable to exist in areas with a combination of high temperature and rainfall in summer, unless diapause eggs enabling survival of these conditions are produced. At Tewkesbury although mean summer temperatures do not exceed 15.6°C, the low R/E value for January may be a key factor in restricting populations there.

Wallace and Mahon (op. cit.) found that the inland or dry limits to the S. viridis distribution in south -western and south-eastern mainland Australia closely followed the 250mm isohyet for the May-October period. The eastern distribution limits in NSW and Victoria approximated the 225m isohyet for the December - March period inclusive. They then state that similar limits are imposed in Tasmania. Although the current survey

shows that the 225mm isohyet does approximate the distribution limits (Fig. 3.4), S. viridis is well established at localities such as Gunns Plains, Sheffield and Redpa in the north-west and around Scottsdale in the north-east in the 250 -260mm December - March isohyet range.

Wallace and Mahon (op. cit.) also found the Australian distribution of S. viridis to be defined approximately by the limits of the Type IV climate of Walter and Lieth (1967). However, use of these parameters in combination with the 800 and 1200mm isohyets to delineate the wet and dry areas of the State (Figs 3.1 and 3.2) was found to be a more useful approximation in defining the S. viridis distribution in Tasmania. The species predominates in those regions with a Type IV climate in the north and north-west and was absent from the high rainfall Type V region on the west coast at Granville Harbour, sub-alpine pastures (Type X climate) and pastures in central eastern areas (Type IV - Type V); as discussed by Wallace and Mahon (1971) low temperatures are probably one of the main restricting factors in these latter 2 areas (Davidson 1934).

In the eastern sector of the Type V zone (Fig. 3.2) (mean annual rainfall < 800 mm) populations were sporadic and those that were located were estimated as low (< $100/m^2$). In these drier areas, sheep are the main grazing animal as opposed to the dairying areas of the north and north-west. Pastures stocked with sheep tend to be grazed shorter than pastures stocked with cattle, and pastures with a good cover of growth would obviously be a more favourable environment than shorter, more exposed pastures particularly in cooler or drier areas of the State. Although no comparative work has been done on pastures grazed by cattle, King and Hutchinson (1976) showed that increased stocking rates of sheep severely reduced the numbers of Collembola, particularly epigaeic species.

Another contributing factor to the non-pest status of S. viridis pasture populations in these localities could also be due to the better adaptation of B. lapidaria to conditions in the central and eastern areas of the State compared to the far north-west where the winters are wetter and warmer.

Since S. viridis is uncommon in pastures in central and eastern areas of Tasmania, B. lapidaria is feeding on other collembolan species or small arthropods. During the surveys, ca 42 epigaeic and hemiedaphic collembolan species which comprise most of the local surface fauna in pastures were identified. Among the most common and widely distributed of these (excluding S. viridis) were Isotomurus palustris (Mueller) group (Isotomidae), Bourletiella viridescens Stach, Katianna australia Womersley, K. oceanica var. schoetti Womersley (Sminthuridae), Entomobrya marginata (Tullberg), E. multifasciata (Tullberg) (Entomobryidae), Hypogastrura spp. (Hypogasturidae) and Brachystomella platensis (Najt and Massoud) (Neanuridae), all of which occurred in pastures with B.

lapidaria (see Chapter 8). Laboratory observations showed that B. lapidaria has a wide host range and it was observed feeding on all of these species with the exception of Hypogastrura spp. and B. platensis. Similar observations on the host range of B. lapidaria were reported by Wallace and Walters (1974) who considered that range versatility enhances the possibility of a predator surviving when its normal prey species is scarce. It appears in central, eastern and probably south-east parts of Tasmania that B. lapidaria is surviving almost entirely on species of Collembola other than S. viridis in pastures.

A significant predator-prey relationship was observed between B. lapidaria and Bourletiella arvalis in South Africa where B. arvalis was dominant collembolan (Wallace and Walters 1974). Such a situation could therefore periodically exist in Tasmania where B. lapidaria populations are well established and any one of the acceptable prey species becomes dominant in local pastures.

CHAPTER 4

THE EFFECTIVENESS OF THE PASTURE SNOUT MITE BDELLODES LAPIDARIA (KRAMER) AS A PREDATOR OF THE LUCERNE FLEA SMINTHURUS VIRIDIS (L.) IN THE PASTURES OF NORTH-WEST TASMANIA

INTRODUCTION

The pasture snout mite, Bdellodes lapidaria (Kramer) was first discovered attacking the lucerne flea, Sminthurus viridis (L.) in Western Australian in 1931 (Womersley 1933a). Currie (1934) then presented evidence which suggested that this predator was controlling populations in some areas where it was originally discovered and his observations were supported by those of Jenkins (1935) and Norris (1938) in Western Australia. Consignments from W.A. were sent to Victoria, South Australia and Tasmania (Currie 1934). However, Pescott (1937) reported that natural populations had been found in several Victorian districts and that they were exerting significant control on S. viridis in at least one of these. Evans (1939) also reported that in Tasmania, where B. lapidaria occurred naturally, it appeared to have a controlling influence on S. viridis populations; however, it did not appear to have a significant effect on S. viridis in any areas where it had been artificially liberated following earlier introductions from Western Australia. There was also no evidence of S. viridis numbers being affected by B. lapidaria at established artificial liberation sites in South Australia (Swan 1940).

Investigations by Wallace (1954a) in Western Australia showed that applications of DDT to pastures caused a substantial increase in S. viridis populations, which was attributed to the reduction in B. lapidaria numbers. Further experiments (Wallace 1967) confirmed that B. lapidaria was significantly influencing S. viridis numbers. A similar predator-prey relationship between numbers of B. lapidaria, S. viridis and another sminthurid, Bourletiella arvalis (Fitch), was shown by Wallace and Walters (1974) following the introduction and establishment of the predator in South Africa.

In Tasmania, the surveys detailed in Chapter 3 showed that B. lapidaria was uncommon in the far north-west, due to unsuitable climatic conditions and was therefore having little influence on S. viridis populations in this area. In order to examine the relationship of B. lapidaria with its prey in other north-west areas, population monitoring commenced at 3 sites in mid-1976. This section (i) describes the changes in numbers of S. viridis and B. lapidaria found at the sites, and (ii) discusses the predator-prey relationships of B. lapidaria in north-west Tasmania and factors which may be affecting these relationships.

MATERIAL AND METHODS

(i) Observation sites

Plots of each of 0.1 ha were selected in pastures infested with S. viridis on Krasnozem soils (pH range 5.0 - 6.0) in north-west Tasmania at Moriarty, Elliott Research Station (Elliott) and Flowerdale in May 1976. All plots were kept unfenced to allow free access of grazing animals. Sampling was continued until autumn 1980; however because of cropping requirements at the original Moriarty (1) site in September 1978, an alternative plot (Moriarty 2) was selected in a neighbouring paddock and

sampled from October 1978. Actual site locations are shown in Fig 3.5 and individual site descriptions are as follows:

(a) Moriarty 1

The sample site was a gently sloping area selected on the north-eastern side of a 4ha paddock. This adjoined other paddocks and was fenced on all four sides apart from some uncleared dry sclerophyll forest in the north-west corner. The dominant sown pasture species were ryegrass (Lolium perenne) and white clover (Trifolium repens) with patches of subterranean clover (T. subterraneum), cocksfoot (Dactylis glomerata) and red clover (T. praetensis). Other grasses noted were Bromus mollis, Poa annua and Hordeum sp. Broad leaf weeds which appeared from time to time consisted mostly of Erodium moschatum, Stellaria media, Taraxacum officinale and Plantago sp. When sampling commenced there was a low incidence of S. viridis (293/m^2) and a population of B. lapidaria at ca 25/m^2. Minor cockchafer damage attributable to Aphodius sp. was noticeable in patches and there was a low incidence of blue oat mite, Penthaleus major (Dugès). The site was used to graze dairy cattle, chiefly in the late winter and spring and occasionally in summer and autumn.

(b) Moriarty 2

This site was chosen in a steep 2 ha paddock with a north-easterly aspect. A large dam surrounded part of the pasture to the north-east with other paddocks adjoining the other (fenced) boundaries. The pasture composition was similar to that described for Moriarty 1. When sampling commenced there was a large population of S. viridis estimated at 51,000/m^2 which had severely damaged the clover component. The population of B. lapidaria at this time was estimated at 51/m^2.

(c) Elliott Research Station (Elliott)

This site was selected in the north-eastern corner of a 3 ha paddock which sloped gradually away to the south-west. The sample site was a flat area of pasture. The four boundaries were fenced from adjoining paddocks on all sides with a hedge of Cupressus macrocarpa dominating the eastern boundary. The dominant sown species were L. perenne and T. repens with smaller patches of T. subterraneum, T. praetensis and D. glomerata. Isolated plants of Arctotheca calendula, Cirsium vulgare, Bellis perennis, T. officinale and Plantago sp. appeared from time to time. The area had been sown to pasture for 6 years and had previously been cropped with barley. The initial S. viridis population was estimated at 980/m^2 and the damage was negligible. No B. lapidaria were counted in the initial sample. Bare patches in the pasture were attributed to the feeding activities of winter corbie, Oncopera rufobrunnea (Tindale) and pasture cockchafer, Aphodius sp., damage was also minor. The pasture was usually heavily grazed twice a year by sheep in spring and autumn.

(d) Flowerdale

The site was selected on a mild slope on the southern boundary of an undulating 3 ha paddock which was bounded to the north by the Bass Highway and to the west and south by a driveway which led to the farm residence. The eastern boundary was fenced from an adjoining paddock. Some sections of this plot were often quite damp and poorly drained compared to the other sites and patches of green herbage (clover) were often observed even during mid-summer. Although the dominant pasture species were as listed for the other sites it did have a noticeably higher proportion of broad leaf weeds particularly Rumex sp. Other common weeds were Plantago sp., Sisymbrium officinale, Erodium moschatum, Stellaria media, Cirsium vulgare and Hordeum murinum. The paddock had been sown to pasture for 4 years and before that used for growing potatoes. When sampling commenced the population of S. viridis was estimated at ca 1120/m^2 but was causing no significant damage. No B. lapidaria were collected in these samples.

(ii) Sampling, counting and analysis

Population monitoring was carried out using the pasture core sample method described in Chapter 2. Counting of S. viridis and B. lapidaria which commenced in May 1976 was extended to include other collembolan species identified at the sites from September 1976 (see Chapter 8), after B. lapidaria had been observed feeding on some of them. Regression analysis of population counts of S. viridis and other common Collembola on those of B. lapidaria were carried out to determine any significant predator-prey relationships

(iii) DDT trial

A study began in March, 1979 to examine collembolan population trends after B. lapidaria numbers were reduced by insecticide spraying. Each plot was divided in half; one half was sprayed with pp'-DDT at the rate of 0.65 L/ha and the other half left as a control. A pre-spray sample of 15 cores was taken from each plot. Sampling was continued at intervals of 14 d until 56 d after spraying, and then resumed at monthly intervals. A 2 m buffer zone was left between the adjacent plots.

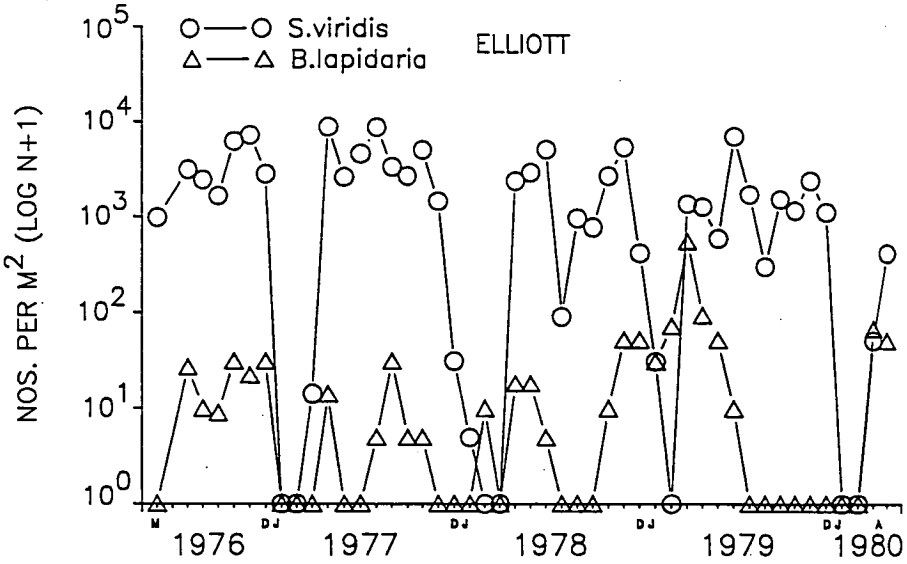
(iv) Meteorological records

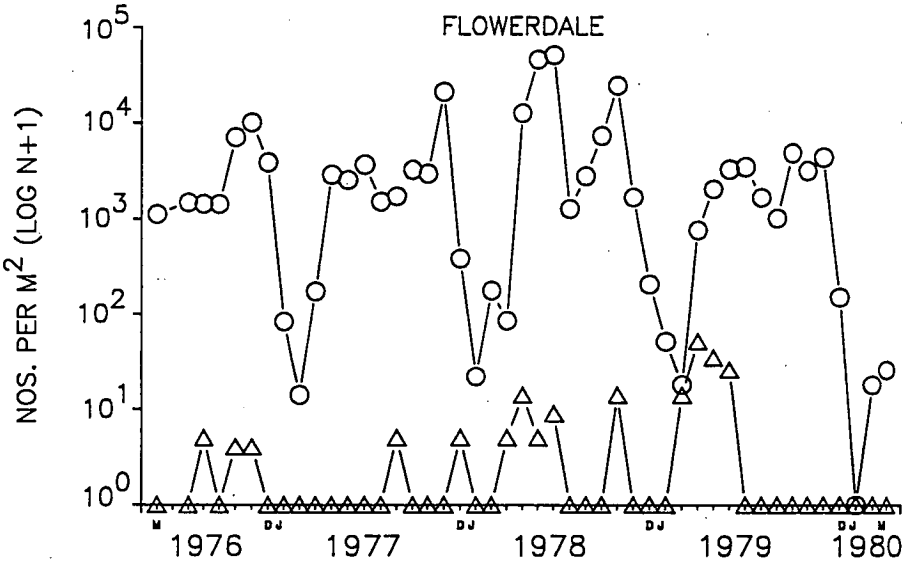
Rainfall and temperature data were obtained through the Bureau of Meteorology from Elliott and from the nearest stations to Flowerdale (Wynyard West) and Moriarty (East Devonport). The latter 2 recording stations were situated within 10 km of the respective sites (Fig 3.5).

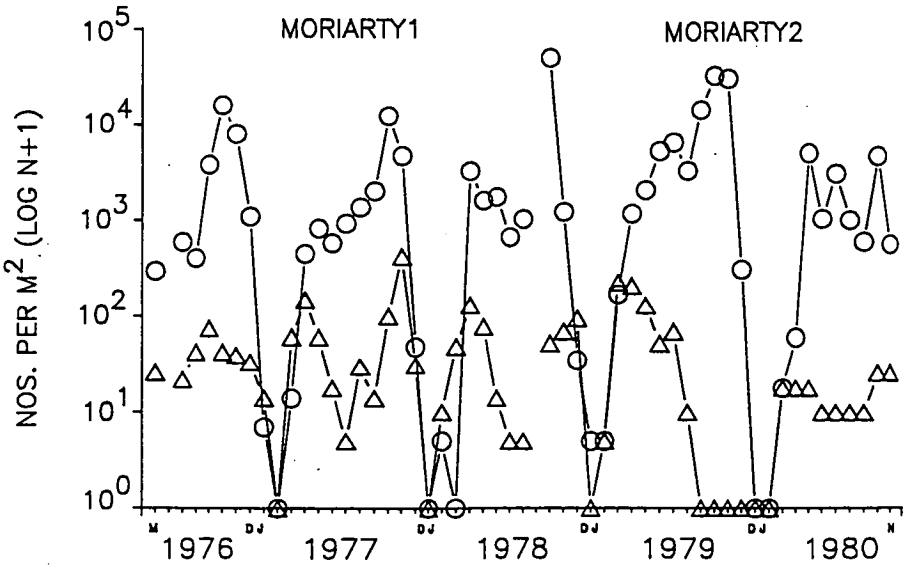
RESULTS

Monthly variations in populations of B. lapidaria and S. viridis at the observation sites from autumn 1976 to autumn 1980 are given in Fig 4.1. Although the largest numbers of S. viridis were most often recorded in spring, activity was always continuous from autumn through winter and

Fig 4.1 Monthly population estimates of B. lapidaria and S. viridis at Elliott, Flowerdale, Moriarty 1 and Moriarty 2 (population estimates after March 1979 are based on counts taken from untreated plots).


S.viridis
B.lapidaria
ELLIOTT
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
DJ
1976
1977
1978
1979
1980


FLOWERDALE
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
DJ
1976
1977
1978
1979
1980


MORIARTY1
MORIARTY2
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
DJ
1976
1977
1978
1979
1980

spring. Populations of the active stages of both S. viridis and B. lapidaria were usually either low or fell to zero at all sites in summer which has been shown by Wallace (1968, 1971) to be a period of egg diapause for both species in Mediterranean-type climates, enabling them to survive hot, dry summer conditions.

Population maxima of B. lapidaria at Moriarty in most cases exceeded those recorded at Elliott and Flowerdale, although S. viridis populations at both Moriarty sites still reached high levels particularly in spring. At Moriarty 1, spring S. viridis densities exceeded 12,000/m^2 on both occasions, even though B. lapidaria densities earlier in the season had exceeded 20/m^2 which contrasted with the observations of Wallace (1967). Active stages of B. lapidaria were present in unusually large numbers at Elliott throughout the spring-summer period of 1978-79 and the largest populations of the predator recorded for Elliott, Flowerdale and Moriarty 2 occurred in March 1979. There was a general tendency at all sites for B. lapidaria numbers to decrease during winter.

The main periods of activity of other collembolan species available as prey to B. lapidaria are shown in Table 4.1. Regression analyses of population counts of S. viridis and these other species against B. lapidaria numbers recorded 4-5 and 8-9 wks earlier in the season failed to indicate any significant relationships.

The effects of DDT on B. lapidaria and surface-active collembolan species common at the sites from 2-8 wks after spraying are presented in Figs 4.2 - 4.4 and are summarised in Table 4.2. Increased numbers of Collembola and decreased numbers of B. lapidaria were recorded in all treated plots. Apart from the mean population increase over the 2-8 wks post-spray period being only slight for I. palustris at Moriarty 2, the increases shown in Table 4.2 ranged from 1.4-3.3 times greater than the control plots. However, pre-spray treatment/control ratios have also been included to indicate increases relative to the population differences prior to treatment.

Rainfall and temperature criteria used in Chapter 3 for discussing the distribution of B. lapidaria are presented for each site in Table 4.3.

DISCUSSION

The lack of a significant predator-prey relationship shows that B. lapidaria was unable to control S. viridis effectively. Examination of Fig. 4.1 also shows there is no clear predator-prey response as there is no general tendency for high S. viridis numbers to be followed by increased populations of B. lapidaria. These results differ from those of Wallace (1967) who obtained a significant negative regression of S. viridis to that of B. lapidaria recorded 8-9 wks earlier in the season and showed that a B. lapidaria density greater than 20/m^2 early in the season was sufficient to prevent an outbreak of S. viridis later in the

Table 4.1 Activity of common surface-active Collembola at monitored sites.

Species	Sites where populations identified*	Main periods of activity (populations exceeding 1000/m^2)**			
		Summer	Autumn	Winter	Spring
Dicyrtomidae					
cf. Dicyrtomina sp. 1	F	-	+	+	+
Sminthuridae					
Sphaeridia pumilis ***	M1,M2	+	+	-	+
(Krausbauer) group					
Katianna australis	E.F	-	+	+	+
Womersley					
Katianna oceanica var.					
schoetti Womersley	E.F	+	+	-	+
Sminthurinus elegans	M2,F	+	+	-	+
(Fitch)					
Bourletiella viridescens	E.F	+	-	-	+
Stach					
Entomobryidae					
Entomobrya marginata	M1,M2	+	+	-	-
(Tullberg)					
Isotomidae					
Isotomurus palustris	M1,M2	-	+	+	+
(Mueller) group	E.F				
Cryptopygus thermophilus ***	M1,M2	+	+	+	+
(Axelson)	E.F				

*E = Elliott; F = Flowerdale; M1 = Moriarty 1; M2 = Moriarty 2

**Other prey or potential prey species recorded at sites (population maxima < 500/m^2) during periods of S.viridis activity were Entomobrya multifasciata (Tullberg) (M1, M2, E, F), S. elegans (E), Katianna mucina Womersley (M2), K. oceanica var. schoetti (M2), K. australia (M2), B. viridescens (M2), and cf. Dicyrtomina sp. 1 (E).

***B. lapidaria has not been observed feeding on these species.

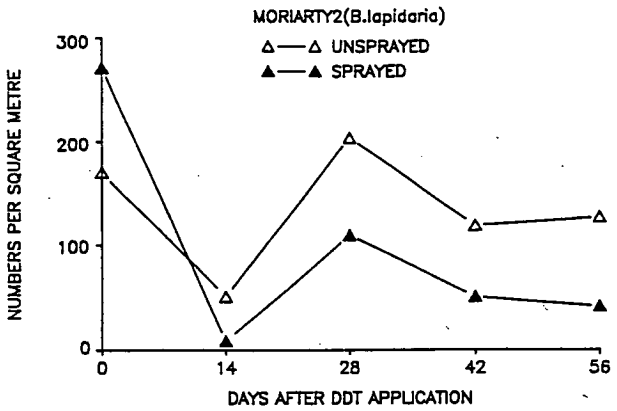
same season. His analyses also revealed a significant positive regression of B. lapidaria numbers on S. viridis numbers recorded 8-9 wks earlier, further indicating a response by the predator to its food source.

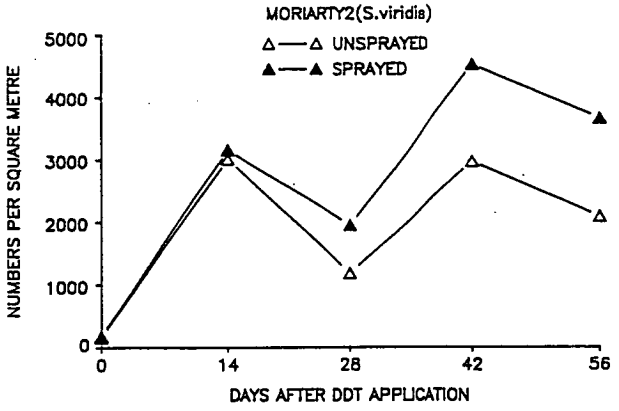
In north-west Tasmania, it appears that the size of B. lapidaria populations is being determined more by the effects of climate than by populations of S. viridis or the abundance of alternative collembolan prey (Table 4.1). The study on the effect of climate on the Tasmanian distribution of B. lapidaria presented in Chapter 3 showed that the predator was rarely found in areas of the far north- west where the mean annual rainfall exceeded 1200 mm and where there was a winter maximum in rainfall and less seasonal fluctuation in temperature (minimum ca 4-6^{o}C in July, maximum 20-22^{o}C in February) than in the drier parts of the State. The rainfall and temperature data (Table 4.3) show that the monitored sites were situated close to these re-defined distribution limits. The consistently larger numbers of B. lapidaria recorded at Moriarty compared to the other sites situated further west suggest a tendency for populations to become lower and even less effective against S. viridis and other prey, as the north- west limits of its distribution are approached.

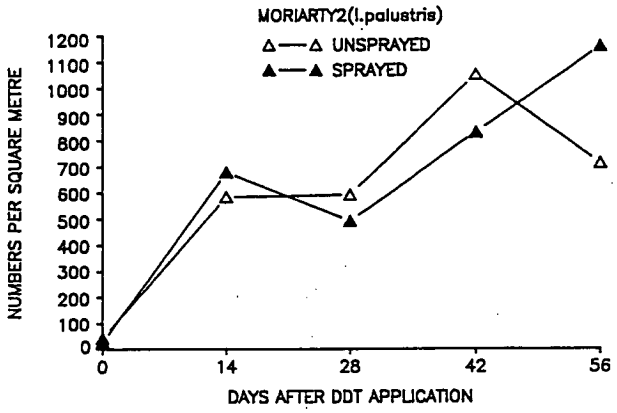
The relatively large populations of B. lapidaria recorded at all sites in March 1979 can be explained in terms of a response to weather conditions. In particular at Elliott, continued activity throughout the previous spring and summer months may have been due to the unusually high January rainfall (100 mm) recorded at this site (117% above mean). However, a temperature factor may also have been involved since the mean temperature from January through to March (16.3^{o}C) was also above the average (15.7^{o}C). It seems a combination of moisture and temperature either stimulated the previously delayed hatching or both; the mites were able to survive throughout the summer probably on E. marginata and B. viridescens, since numbers both exceeded 100/m^{2} during this period. Similar rainfall and temperature trends were also recorded from Moriarty and Flowerdale and may also have been responsible for the relatively large autumn populations at these sites, i.e. weather factors were suitable for diapause development enabling simultaneous hatching of a large number of eggs.

Studies on the predatory efficiency of B. lapidaria on S. viridis reported by Wallace (1967) indicated the predator is more likely to be effective when there is a high proportion of young nymphs available, since large nymphs and adults are more difficult to catch. This is an important factor to consider in relation to climate. The south-western corner of Western Australia where S. viridis was shown by Wallace (1967) to be controlled by B. lapidaria are subjected to a Mediterranean-type climate with a long summer drought season.

Fig 4.2 Population estimates of B. lapidaria, S. viridis, I. palustris and E. marginata in sprayed and unsprayed plots at Moriarty 2 (before spraying and 2-8 weeks post-spraying).


MORIARTY2(B.lapidaria)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
300
200
100
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


MORIARTY2(S.viridis)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
5000
4000
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


MORIARTY2(I.palustris)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION

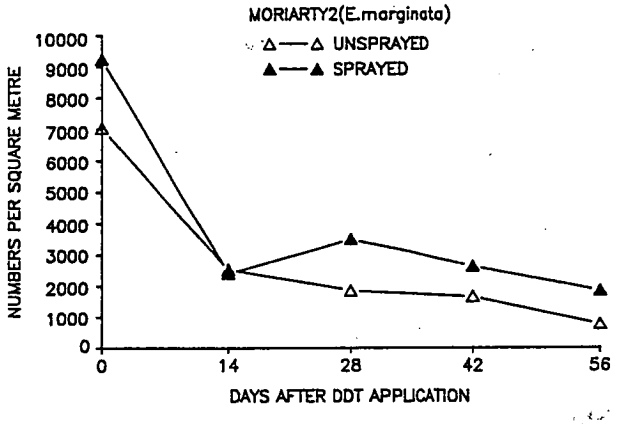
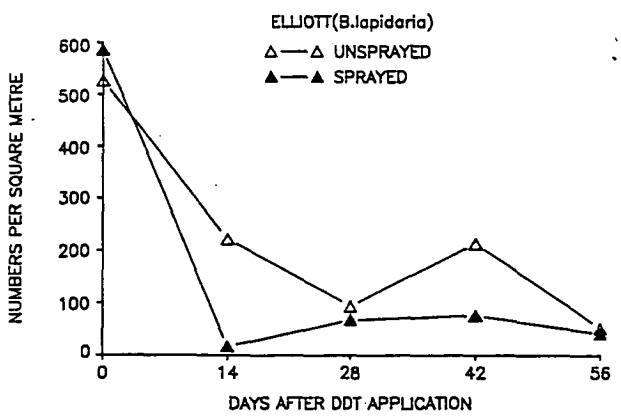
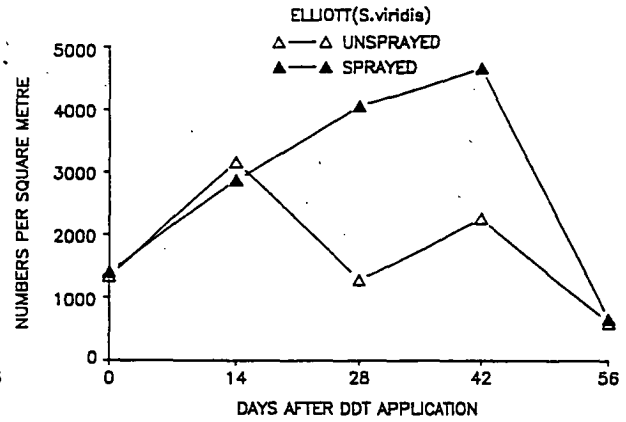
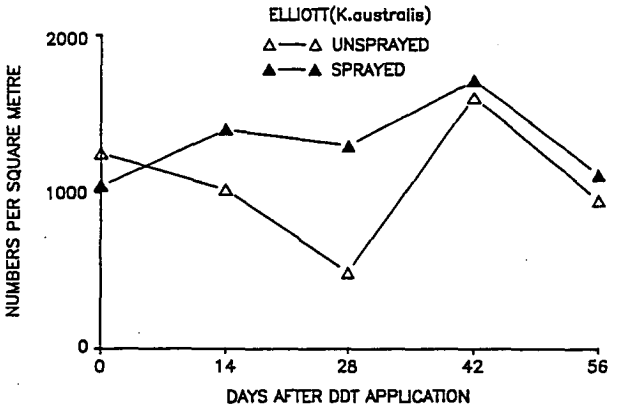
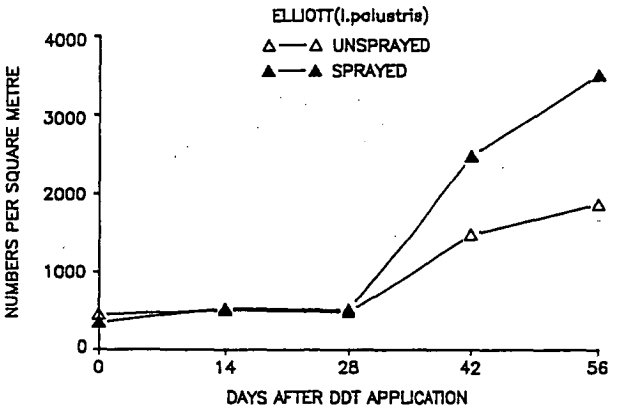

MORIARTY2(E.marginata)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION

Fig 4.3 Population estimates of B. lapidaria, S. viridis, K. australis, I. palustris and E. marginata in sprayed and unsprayed plots at Elliott (before spraying and 2-8 weeks post-spraying).


ELLIOTT(B.lapidaria)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
600
500
400
300
200
100
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


ELLIOTT(S.viridis)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
5000
4000
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


ELLIOTT(K.australis)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


ELLIOTT(I.palustris)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
4000
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION

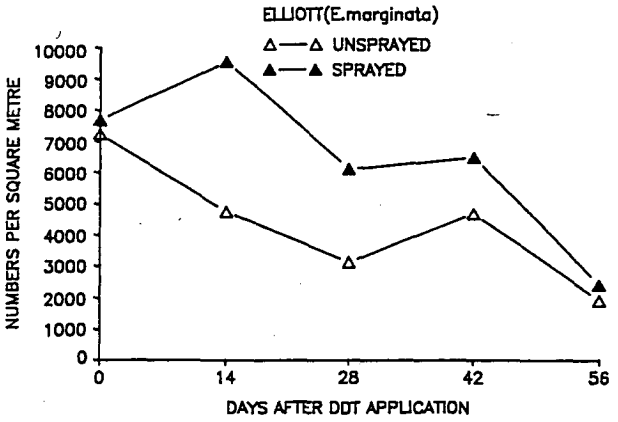
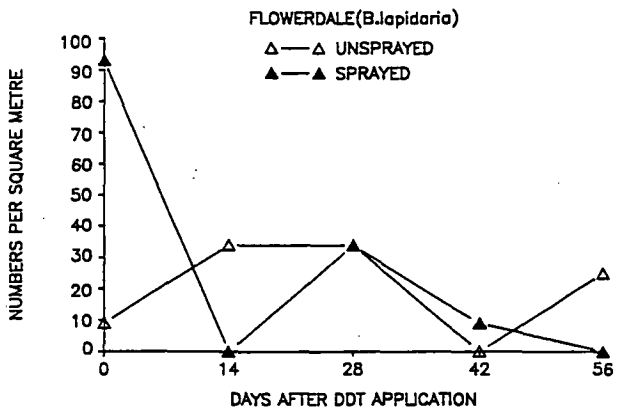
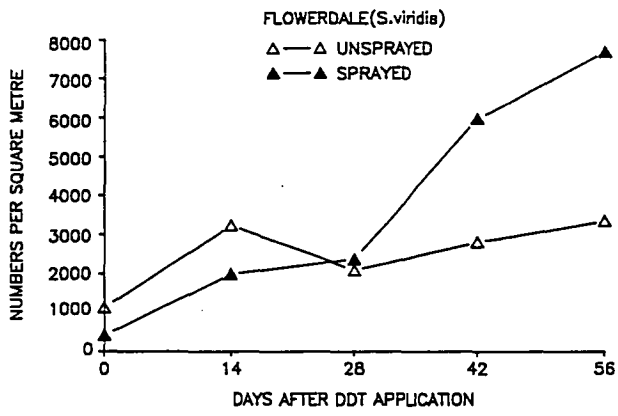
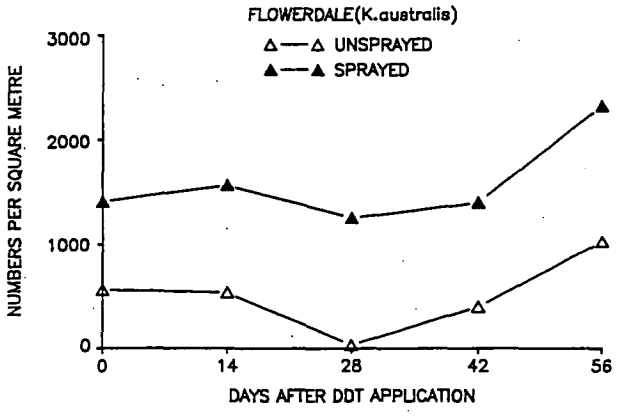
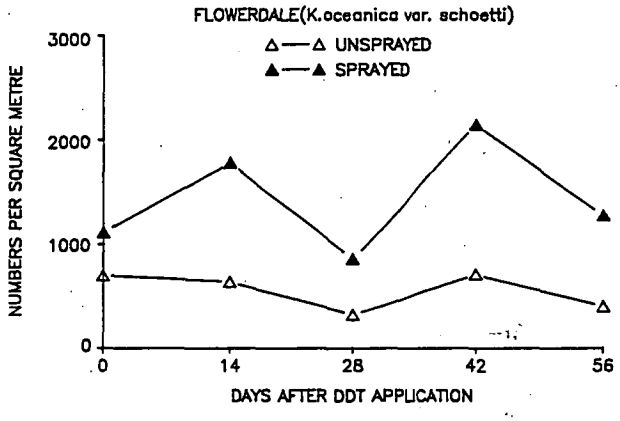

ELLIOTT(E.marginata)
UNSPRAYED
SPRAYED
NUMBERS PER SQUARE METRE
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION

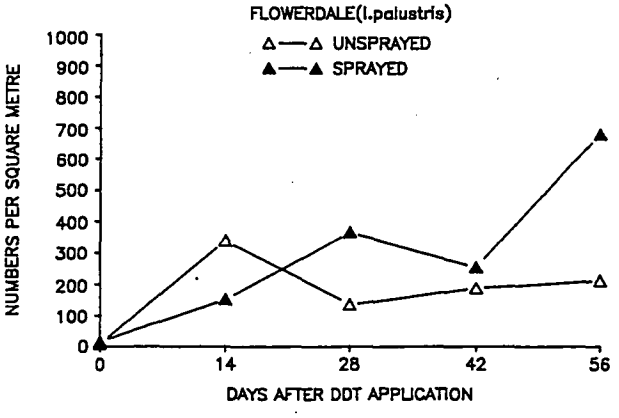
Fig 4.4 Population estimates of B. lapidaria, S. viridis, K. australia, K. oceanica var. schoetti, I. palustris and E. marginata in sprayed and unsprayed plots at Flowerdale (before spraying and 2-8 weeks post-spraying).


FLOWERDALE(B.lapidaria)
△—△ UNSPRAYED
▲—▲ SPRAYED
NUMBERS PER SQUARE METRE
100
90
80
70
60
50
40
30
20
10
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


FLOWERDALE(S.viridis)
△—△ UNSPRAYED
▲—▲ SPRAYED
NUMBERS PER SQUARE METRE
8000
7000
6000
5000
4000
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


FLOWERDALE(K.australis)
△—△ UNSPRAYED
▲—▲ SPRAYED
NUMBERS PER SQUARE METRE
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


FLOWERDALE(K.oceanica var. schoetti)
△—△ UNSPRAYED
▲—▲ SPRAYED
NUMBERS PER SQUARE METRE
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION


FLOWERDALE(I.palustris)
△—△ UNSPRAYED
▲—▲ SPRAYED
NUMBERS PER SQUARE METRE
1000
900
800
700
600
500
400
300
200
100
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION

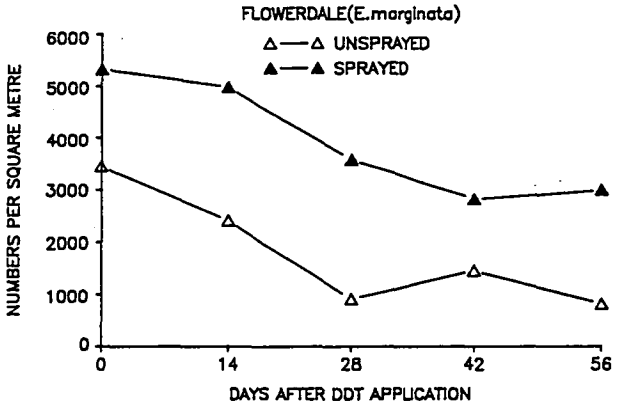

FLOWERDALE(E.marginata)
△—△ UNSPRAYED
▲—▲ SPRAYED
NUMBERS PER SQUARE METRE
6000
5000
4000
3000
2000
1000
0
0
14
28
42
56
DAYS AFTER DDT APPLICATION

Table 4.2 Comparative densities of B. lapidaria and common Collembola in treated and control plots, expressed as the ratio (treatment/control) of population counts (mean no./m^2) before spraying* and 2-8 weeks post-spray.**

Species***	Moriarty		Elliott		Flowerdale	
	Pre-spray	Post-spray	Pre-spray	Post-spray	Pre-spray	Post-spray
B. lapidaria	1.6	0.4	1.1	0.3	10.3	0.5
S. viridis	1.1	1.4	1.1	1.7	0.4	1.6
K. australis	-	-	0.8	1.4	2.5	3.3
Katianna oceanica var.schoetti	-	-	-	-	1.6	2.9
E. marginata	1.3	1.5	1.1	1.7	1.5	2.6
I. palustris	0.6	1.1	0.8	1.6	1.0	1.7

*Mean of populations sampled on 26.3.79.
**Mean of populations sampled on 9.4.79, 23.4.79, 7.5.79 and 21.5.79.
***Species included only if population maxima during trial period exceeded 1000/m^2 in sprayed and unsprayed plots.

Table 4.3 Comparison of long term means of annual rainfall, December-March isohyets and temperature extremes for Moriarty, Elliott and Flowerdale.

	Mean annual rainfall (mm)	Mean Dec.-Mar. isohyet (mm)	Mean Jul. min.(°C)	Mean Feb. max.(°C)
Moriarty	884	205	3.2	21.3
Elliott	1203	244	4.3	21.0
Flowerdale	1031	216	3.7	21.8

This ensures that when the rains arrive in autumn a synchronised hatch of nearly the whole population occurs which consists entirely of small nymphs highly susceptible to predation by B. lapidaria and perhaps other predators. In north- west Tasmania, however, the cooler wetter, climate throughout the year results in a greater overlap of generations. As a result the hatching that takes place in autumn is staggered unless there is an unusually long dry summer. Examination of S. viridis individuals at the sample sites on any sample date always revealed considerable variation in the age of individual specimens ranging from young nymphs to adults. A proportion of the population at any one time is therefore nearly always outside the predator range of B. lapidaria, thus reducing its predation efficiency.

Apart from climatic factors, the effect of abundance of alternative collembolan prey on the performance of B. lapidaria as a predator of S. viridis should be considered. Wallace and Walters (1974) showed that B. lapidaria readily eats other collembolan species and discussed the apparent preference of B. lapidaria for S. viridis as being due only to the numerical dominance of this species. They also discussed the value of a general predator such as B. lapidaria being able to feed on other species during periods when its main source of prey was either absent or in low numbers. In north-west Tasmania however, the seasonality and abundance of alternative prey species may cause the predation effectiveness of B. lapidaria on S. viridis to be reduced. If most of a numerically dominant S. viridis population consisted of nymphs and adults above the predation range of B. lapidaria, then populations of less dominant smaller species could be more liable to attack. The size of adults of the sminthurid Collembola listed in Table 4.1 range from ca 0.3 to 1.5 mm, compared to 2.0-2.5 mm for adult S. viridis and although adults of E. marginata and I. palustris appear in this latter size range, the possibility exists for species other than S. viridis to become the preferred prey of B. lapidaria on the basis of size.

The results of the DDT trial (Table 4.2) also suggest that S. viridis, even though it was numerically dominant to other species, is not necessarily the preferred prey, since other species showed similar population increases. Wallace (1967) reported increases in the average density of S. viridis numbers in DDT sprayed plots from 1.3 to 8 times in Western Australia due to reduction in numbers of B. lapidaria which was the only effective predator at the site; other prey species were not mentioned. No increases in S. viridis were noted in sprayed plots where B. lapidaria was absent, the only other predators recorded being other bdellid species (mainly the endemics B. affinis Atyeo and B. harpax Atyeo) present in small numbers.

In north-west Tasmania, although B. lapidaria was the dominant mite predator during the spray trials, other collembolan predator species including species of mesostigmatid mites exist, and their role is

discussed in Chapter 5. Increases in collembolan populations as the result of decreases in populations of mesostigmatid predators by DDT spraying was discussed by Sheals (1956) and Edwards et al. (1967a), so it is possible that in the north-west, DDT applications could cause increases in surface-active populations even if B. lapidaria was absent.

However, the poor control of S. viridis by B lapidaria confirms the conclusion from the surveys reported in Chapter 3, that new introductions of climatically pre-adapted predators should be investigated.

CHAPTER 5

FURTHER OBSERVATIONS ON MITE PREDATORS OF SMINTHURUS VIRIDIS (L.) AND OTHER COLLEMBOLA IN THE TASMANIAN CULTURE STEPPE WITH PARTICULAR REFERENCE TO SPECIES INHABITING IMPROVED PASTURE FROM THE FAMILIES ANYSTIDAE AND PARASITIDAE

INTRODUCTION

During the field studies on B. lapidaria reported in Chapters 3 & 4, other mite predators from the families Anystidae and Parasitidae were observed feeding on Collembola. Other bdellid mites were also identified during the field surveys. To obtain information on their Tasmanian distribution and significance in the collembolan predator complex in pastures, collections of parasitid, anystid and bdellid species (additional to B. lapidaria) were made during field surveys and included with data analyses used for B. lapidaria and Collembola. In addition, population monitoring of parasitid and anystid mites commenced in early 1979, in conjunction with the monitoring studies on Collembola and B. lapidaria populations already being carried out at Moriarty, Elliot Research Station and Flowerdale. This Chapter reports on the results of this work and (i) identifies the mite predators collected, (ii) provides information on their distribution and seasonal occurrence and (iii) discusses their significance as collembolan predators with particular reference to S. viridis

MATERIALS AND METHODS

Collections during field surveys and at monitored sites, clearing, mounting and identification procedures are described in the general materials and methods section in Chapter 2. Most collections were made in pastures and species distribution was examined in relation to wet and dry pasture ecotypes and climatic zones as defined in Chapter 3. Distribution of species between wet and dry pasture ecotypes was determined using the log-linear method as is done for data presented in Chapters 3, 8 and 12.

To observe population trends, counts of parasitid and anystid mites were taken over a 12 month period from April 1979 at Moriarty 2 and Flowerdale, and from May 1979 at Elliot Research Station. Parasitidae collected during surveys were identified to species, however, because of the time involved no attempt was made to separate species in monthly collections from monitored plots. Monthly counts of Parasitidae were compared to numbers of surface-active Collembola 4-5 and 8-9 weeks after numbers of Collembola were counted. A regression analysis was carried out on the data to determine any significant predator-prey relationships.

Note was taken of any acarine species observed feeding on Collembola in the field, or during observations of live field collected material on sorting trays in the laboratory. Where possible the collembolan on which the predator was feeding was identified.

RESULTS

The list of anystid, bdellid and parasitid mite species identified from the Tasmanian culture steppe is given in Table 5.1. The results show that the most common bdellid in Tasmanian pastures other than B. lapidaria (Fig. 5.1) is Cyta latirostris. In comparison to both these species,

Table 5.1 Collection records[+] of Anystidae, Bdellidae* and Parasitidae from the Tasmanian Culture Steppe

Identification	No. records from surveys of 239 pastures	No. additional pasture records	Field crops	Horticulture (orchards, vineyards)	Other (grasses, weeds, lawns)	Total records
Anystidae						
Anystis baccarum L.	26	9	3	1	2	41
Bdellidae*						
Odontoscirinae						
Bdellodes affinis Atyeo	8	1	0	0	1	10
Bdellodes currax Atyeo	2	5	0	0	1	8
Bdellodes hadroseta Wallace & Mahon	1	0	0	0	0	1
Bdellodes harpax Atyeo	2	0	0	0	1	3
Bdellodes meridionalis Thor.	1	0	0	0	0	1
Bdellodes tasmaniensis Wallace & Mahon	0	4	0	0	4	8
Cytinae						
Cyta latirostris (Hermann)	58	10	2	2	4	76
Spinidellinae						
Spinidella sp.	0	2	0	0	0	2
Parasitidae						
Pergamasus (Pergamasus) longicornis Berlese	100	8	0	0	0	108
Pergamasus (P.) quisquiliarum (Canestrini)	30	6	0	0	0	36

[+]Majority of records are of collections made by Ireson from 1975 to 1988, some additional records were obtained from Tasmanian Department of Agriculture museum collection (New Town Laboratories). Bdellid surveys by Wallace and Mahon (1976) are not included.

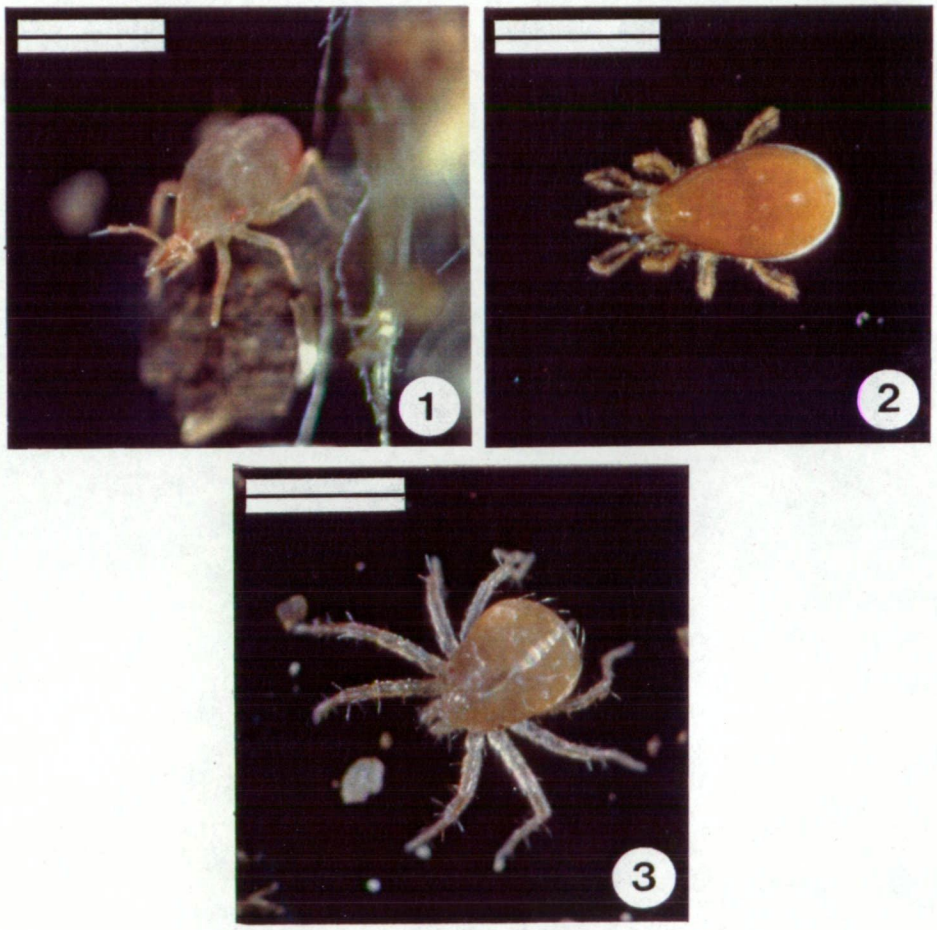
* Excluding Bdellodes lapidaria (Kramer) (data for this species is presented in Chapter 3).

other bdellids were uncommon. The genus Spinidella was identified from Tasmania for the first time but was rare and collected from only one site. P. longicornis was the most common of the two species of Parasitidae identified (Fig. 5.2) and a third unidentified Pergamasus species was also collected. The only anystid, A. baccarum (Fig 5.3), had also not previously been recorded from pastures in this State. Localities where the Pergamasus spp., A. baccarum, C. latirostris and bdellids (other than B. lapidaria) were identified are presented in the maps in Figs 5.4 - 5.11 from the collection data in Table 5.1. Pasture ecotype preferences are indicated in Table 5.2. P. longicornis exhibited a significant preference for the wet pasture ecotype and C. latirostris showed a similar distribution to B. lapidaria (Chapter 3) being uncommon in the wetter far north-west region of the State, and exhibiting a significant preference for the drier pasture ecotype. No significant preference is indicated by A. baccarum or P. quisquiliarum although preferences may have been masked by their lower frequency. No analysis of collection data to determine distribution preferences for the remaining bdellid species was attempted because of their low frequency, however Figs 5.9, 5.10, 5.12 and 5.13 show that collections of B. currax, B. hadroseta, B. meridionalis and B. tasmaniensis were mostly from high rainfall areas.

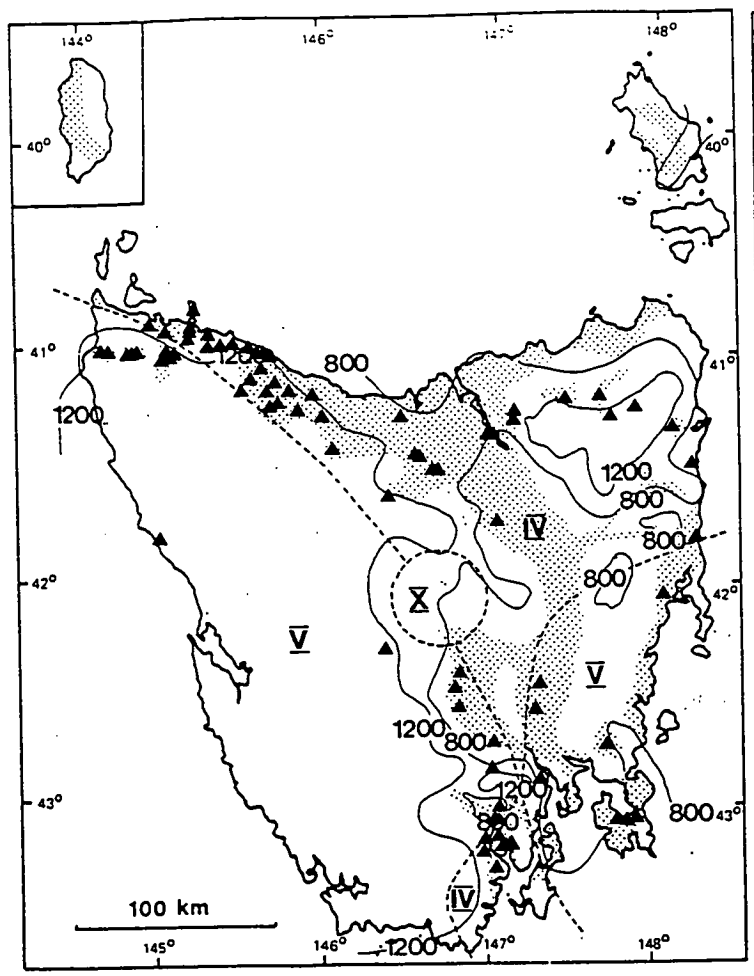
Survey collection results (Table 5.2) showed significant seasonal trends for both A. baccarum and P. longicornis, A. baccarum being identified mostly from samples taken in summer and P. longicornis from samples taken in autumn and spring. Data obtained on A. baccarum from monitored sites (Fig 5.15) confirm the survey results, the species showing a distinct summer maximum, actually commencing in Spring and continuing into Autumn. Population maxima of Parasitidae at monitored sites (Fig. 5.16) were usually recorded in autumn and spring months, although maximum levels at Flowerdale were recorded in mid-December. Only Parasitidae and A. baccarum were observed feeding on Collembola either in the field or in the laboratory. P. longicornis males were observed feeding on S. viridis, Sminthurinus spp. (Sminthuridae), Entomobrya multifasciata, E. marginata (Entomobryidae) and Isotomurus palustris (Isotomidae) indicating a wide collembolan host range. A. baccarum was observed to be more voracious than the other mite predators of Collembola (including B. lapidaria), fast moving and efficient in obtaining its prey. Species on which it was observed feeding were S. viridis, Katianna ornata, Bourletiella viridescens, Sminthurinus spp. (Sminthuridae), E. marginata, E multifasciata (Entomobryidae) and I. palustris (Isotomidae).

Regression analysis of numbers of Parasitidae against numbers of Collembola recorded earlier in the season gave no indication of a significant predator - prey relationship.

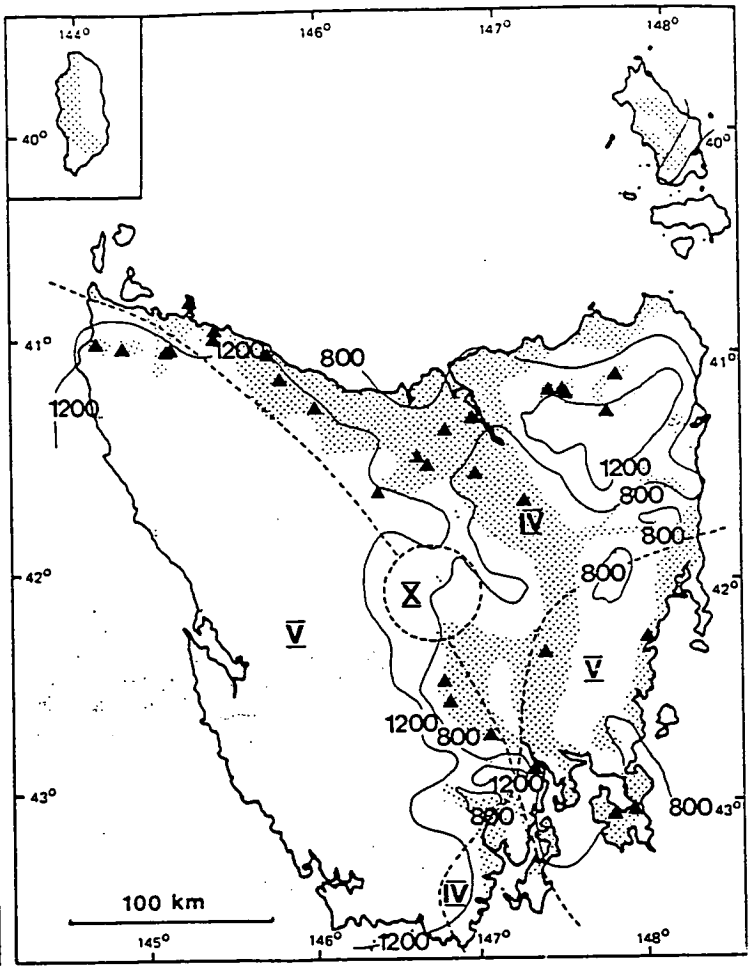
Figs 5.1 - 5.3 Mite predators of *S. viridis*: (1) adult *B. lapidaria* (live specimen); (2) adult *P. longicornis* (live specimen); (3) adult *A. baccarum* (live specimen). Scale lines 1 mm.


1
2
3

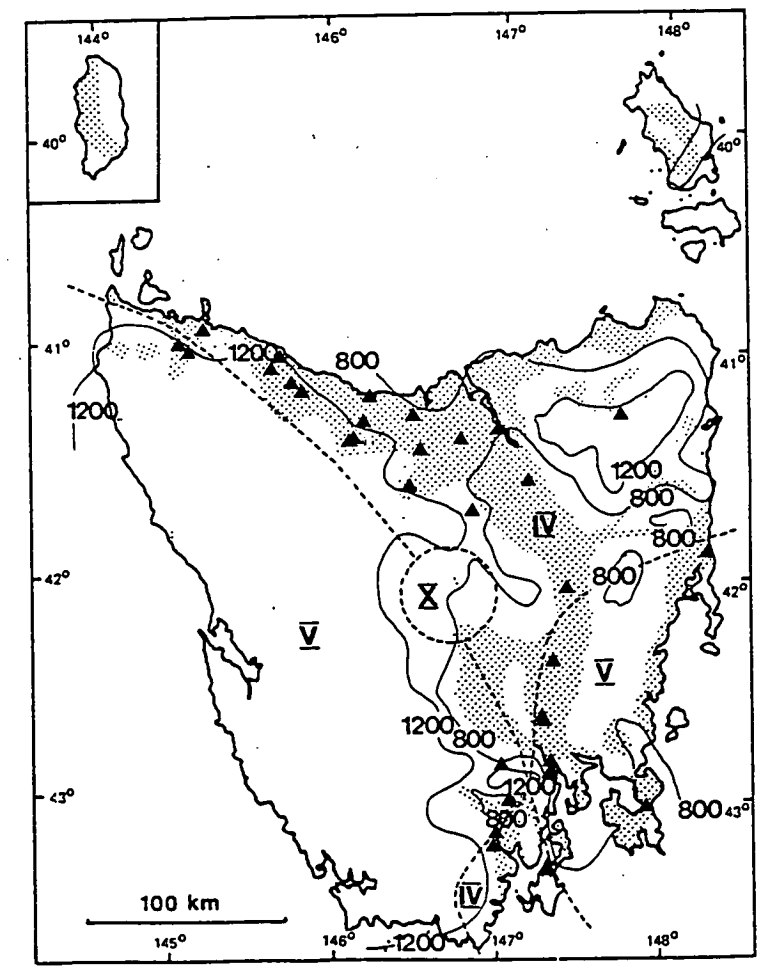
Figs 5.4 - 5.14 Collection sites for parasitid, anystid and bdellid mites in Tasmanian pastures in relation to the climatic zones of Walter and Lieth (1967) and the 800 and 1200 mm annual isohyets (stippling on each map is equivalent to the approximate area of sown pasture ca 900,000 ha).



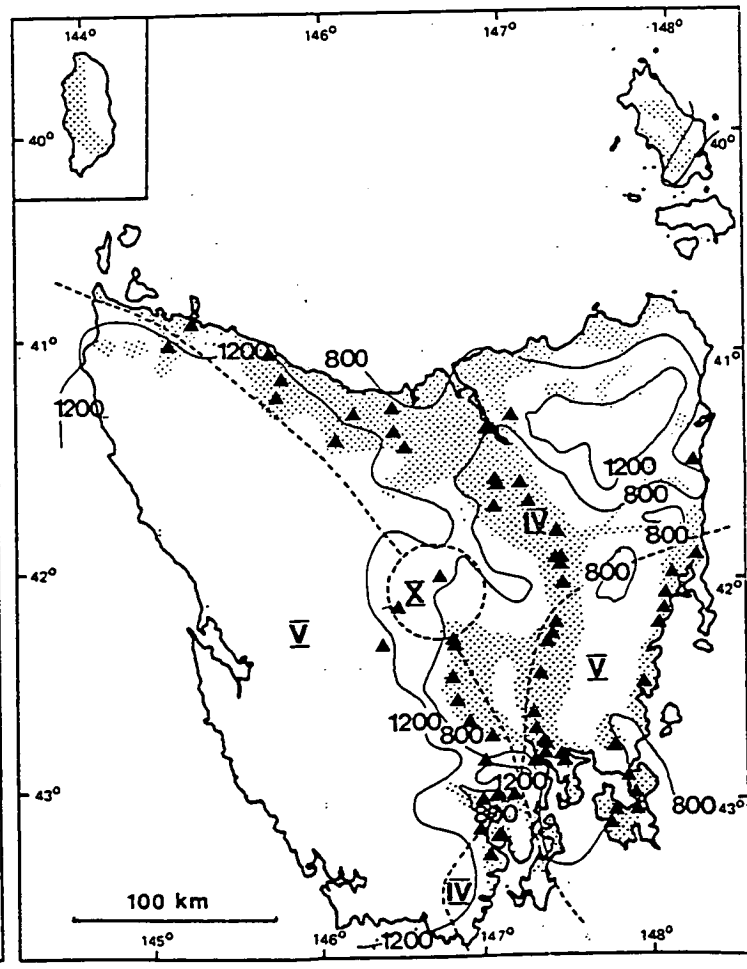
5.4. *P. longicornis*



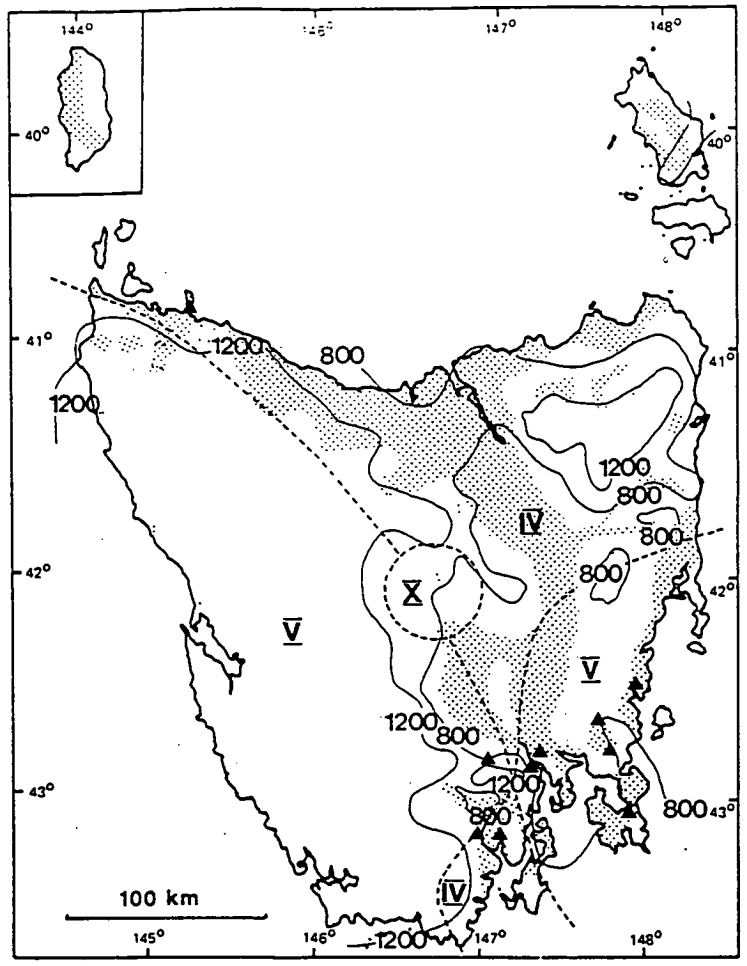
5.5. *P. quisquiliarum*



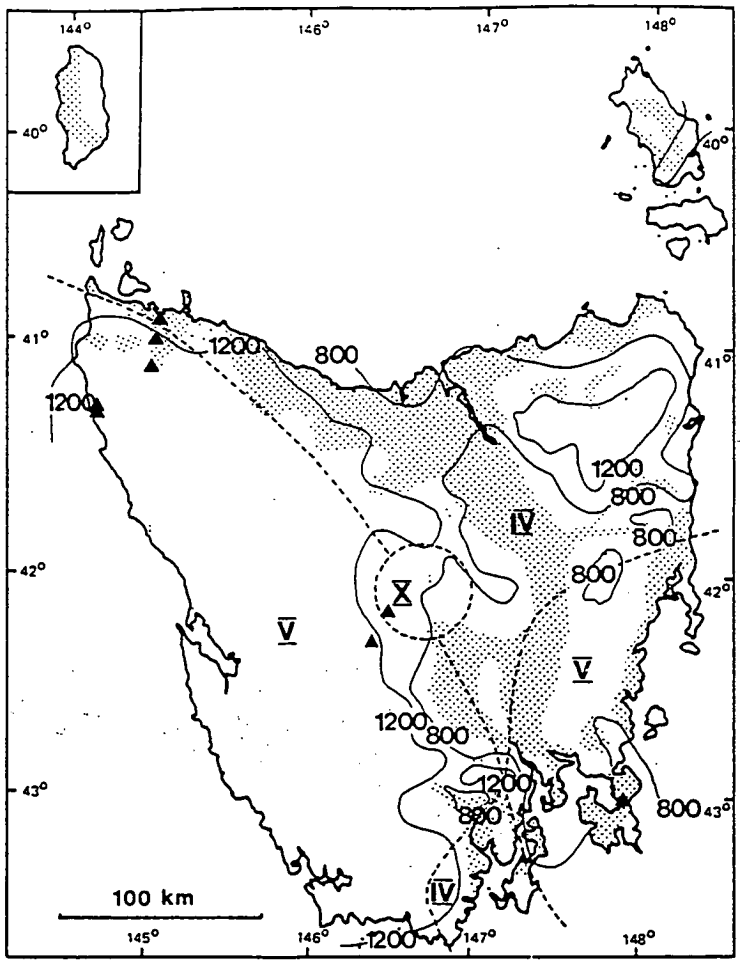
5.6. *A. baccarum*



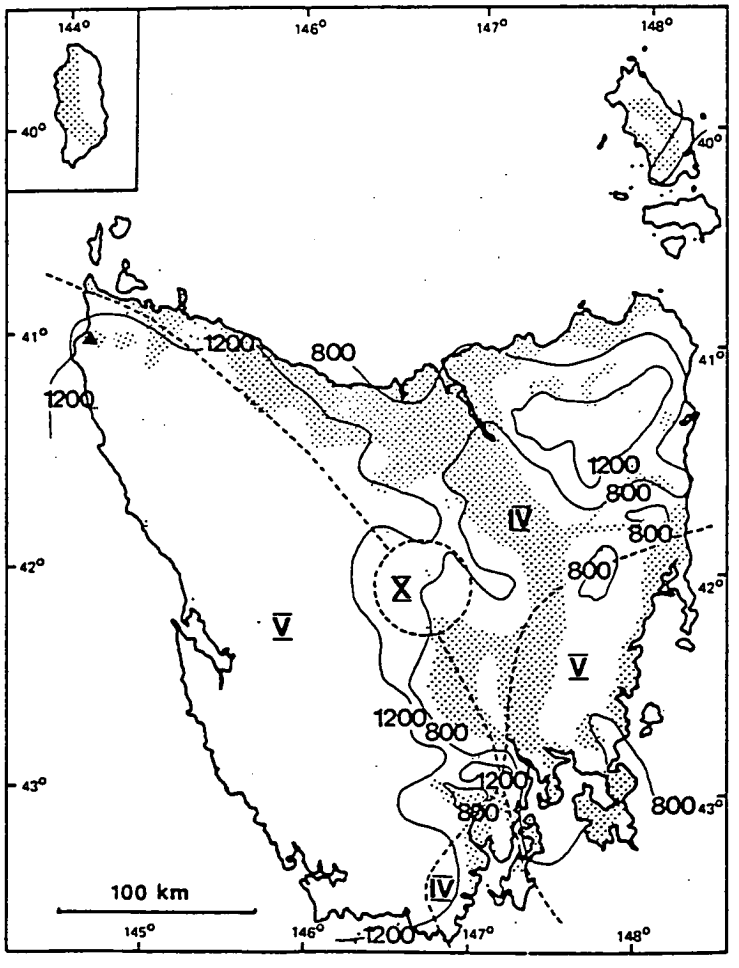
5.7. *C. latirostris*



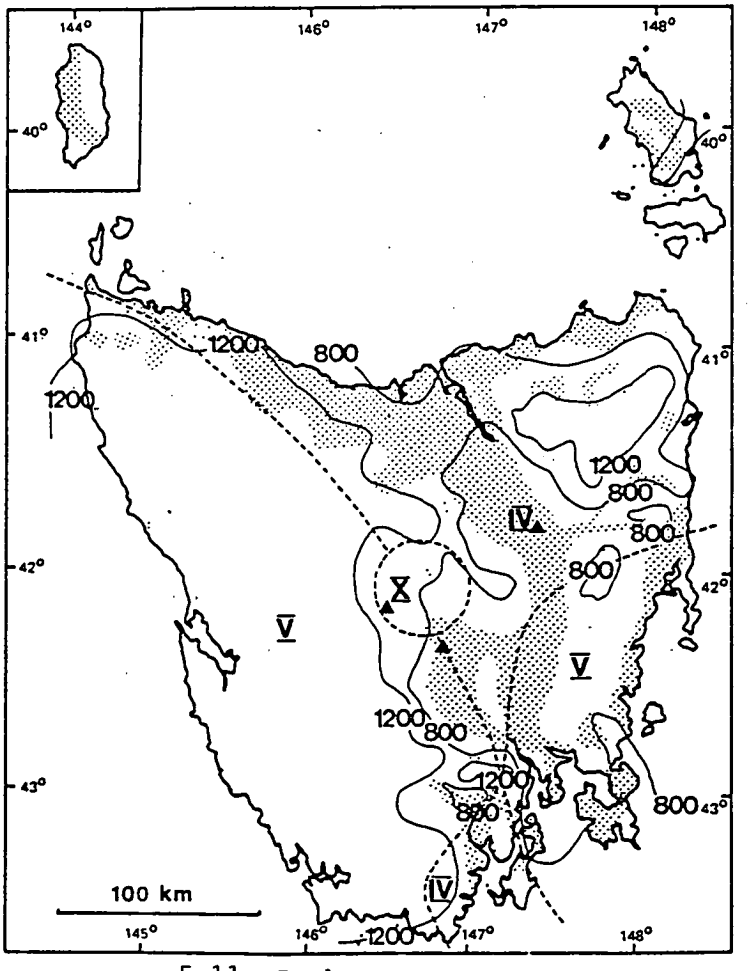
5.8. *B. affinis*



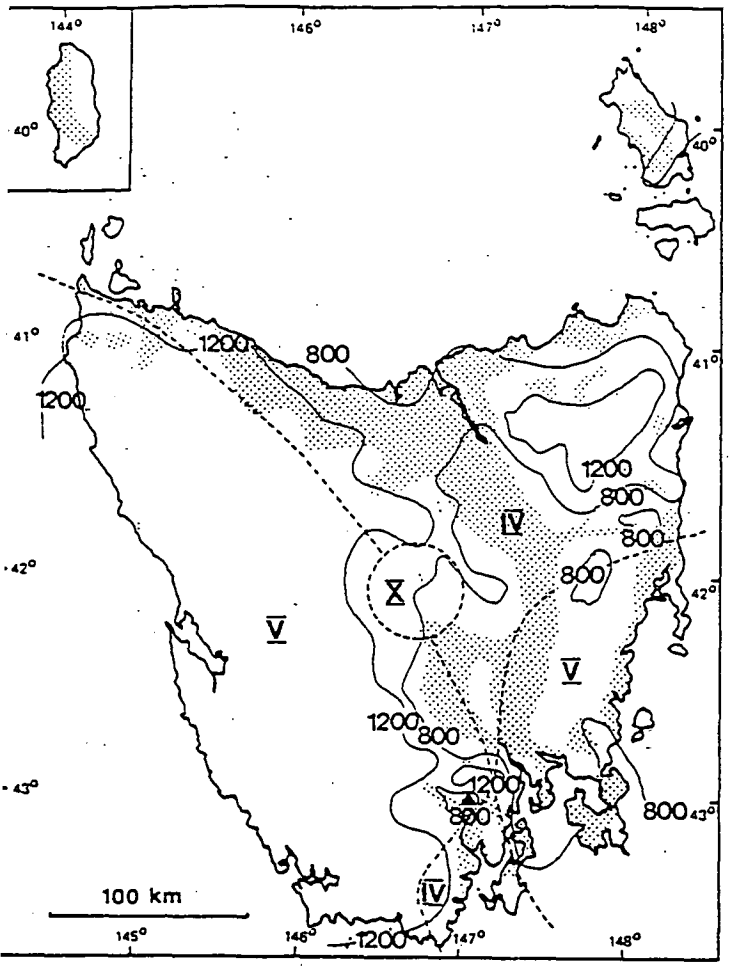
5.9. *B. currax*



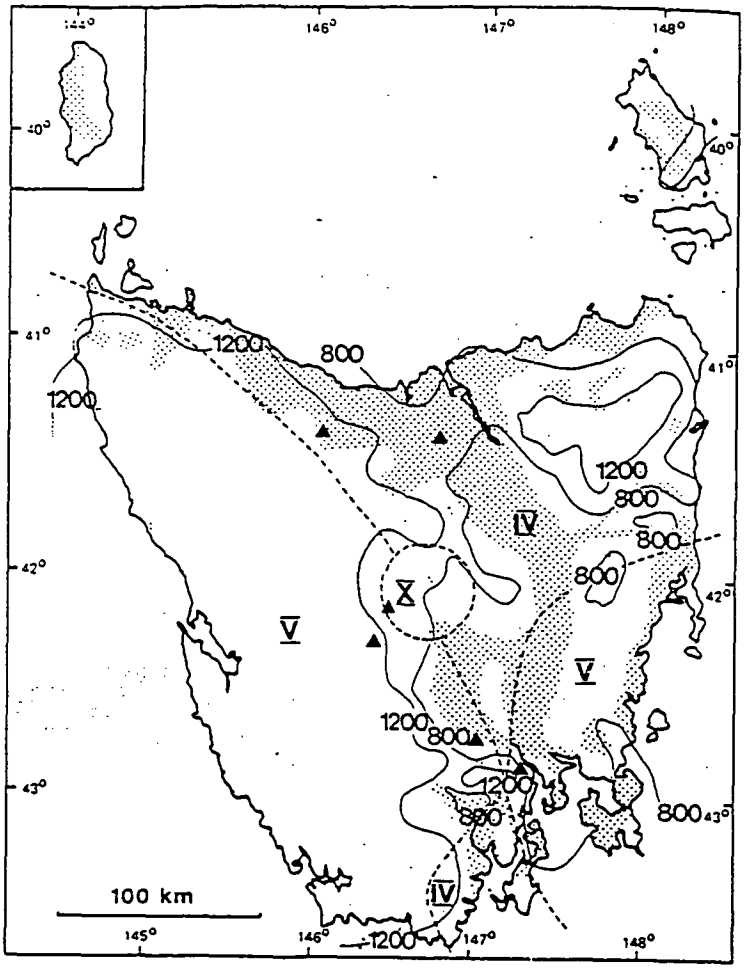
5.10. *B. hadroseta*



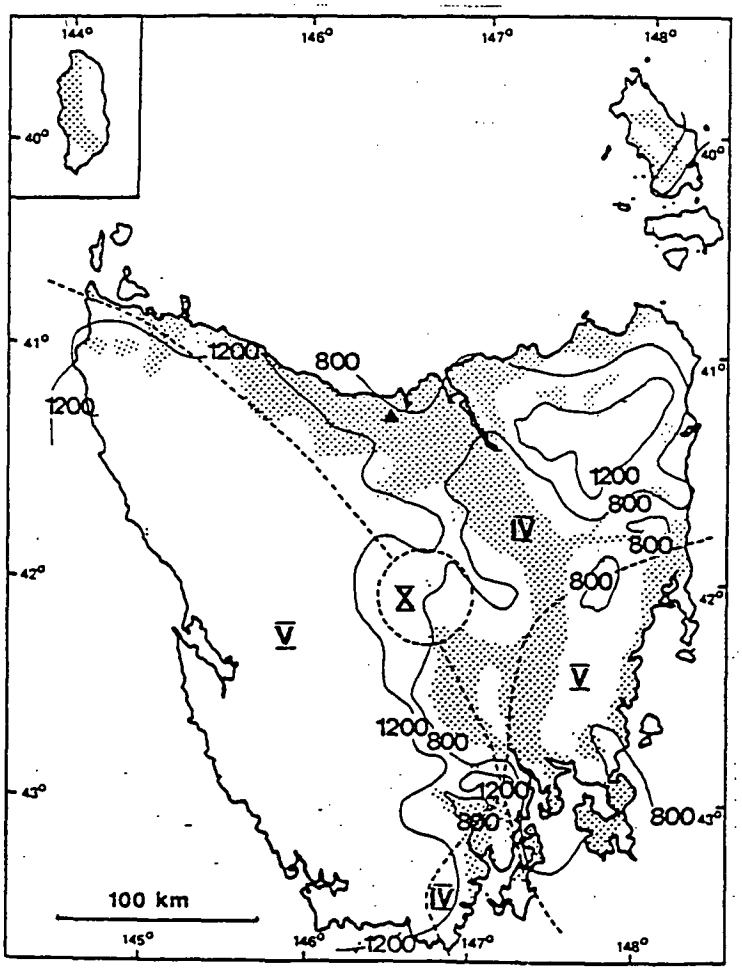
5.11. *B. harpax*



5.12. *B. meridionalis*

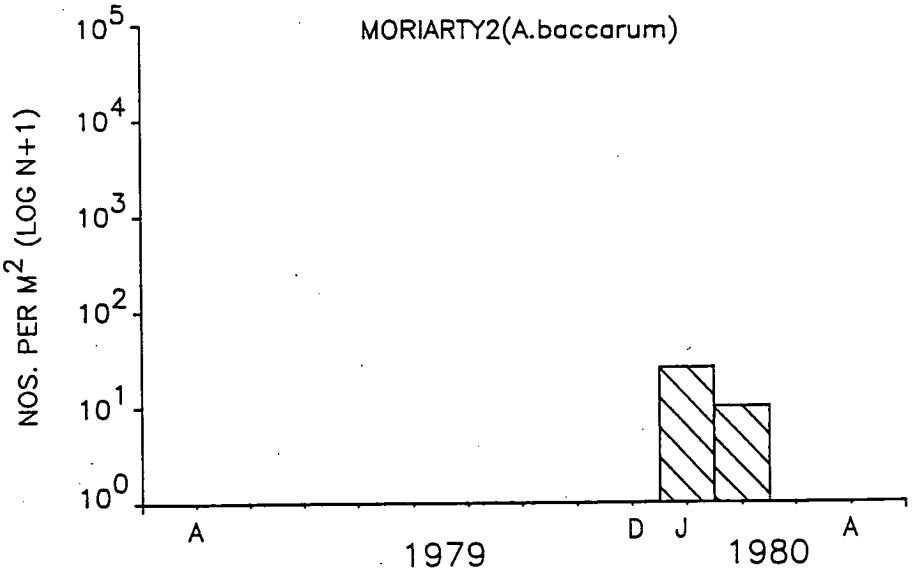


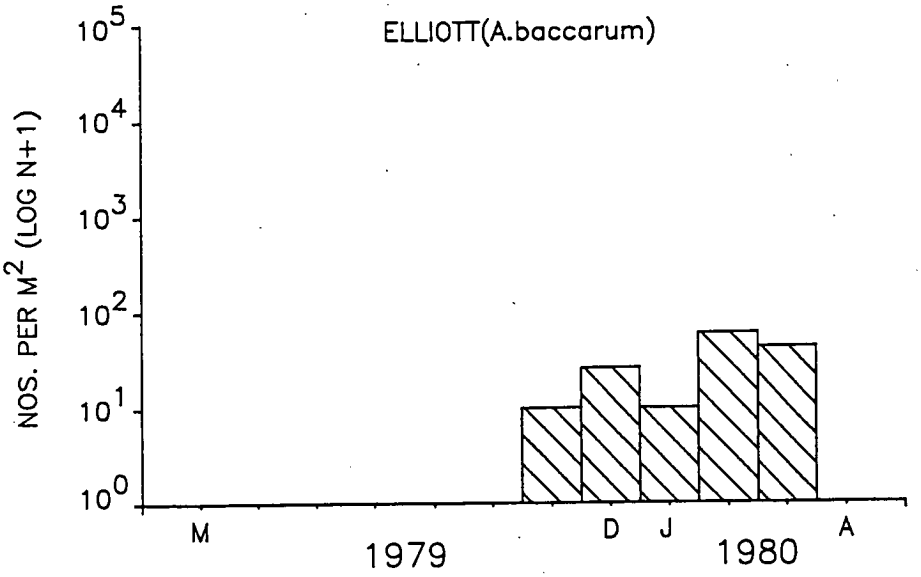
5.13 *B. tasmaniensis*



5.14. *Spinidella* sp.

Fig. 5.15 Monthly population estimates of A. baccarum at Moriarty 2, Elliott and Flowerdale (1979-1980).


MORIARTY2(A.baccarum)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
A
1979
D
J
1980
A


ELLIOTT(A.baccarum)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
1979
D
J
1980
A

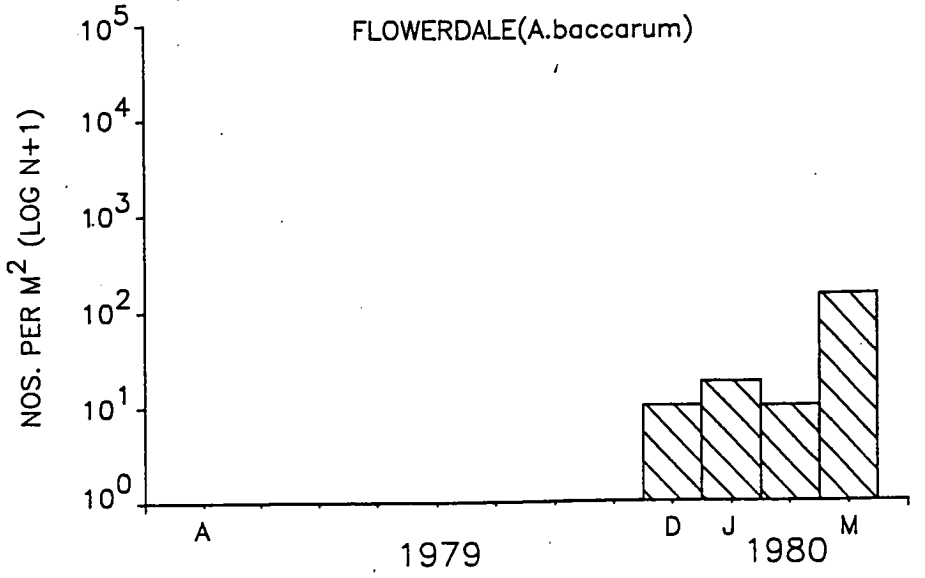
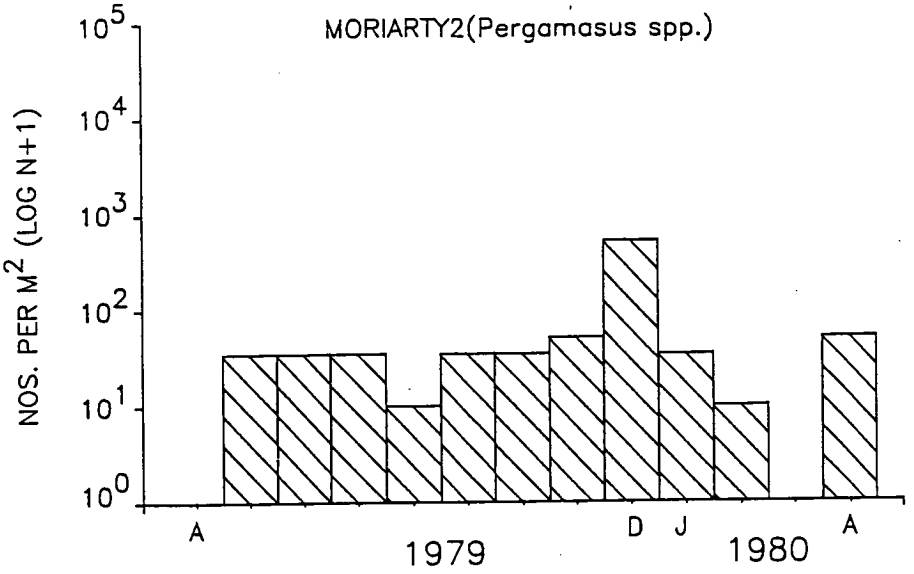
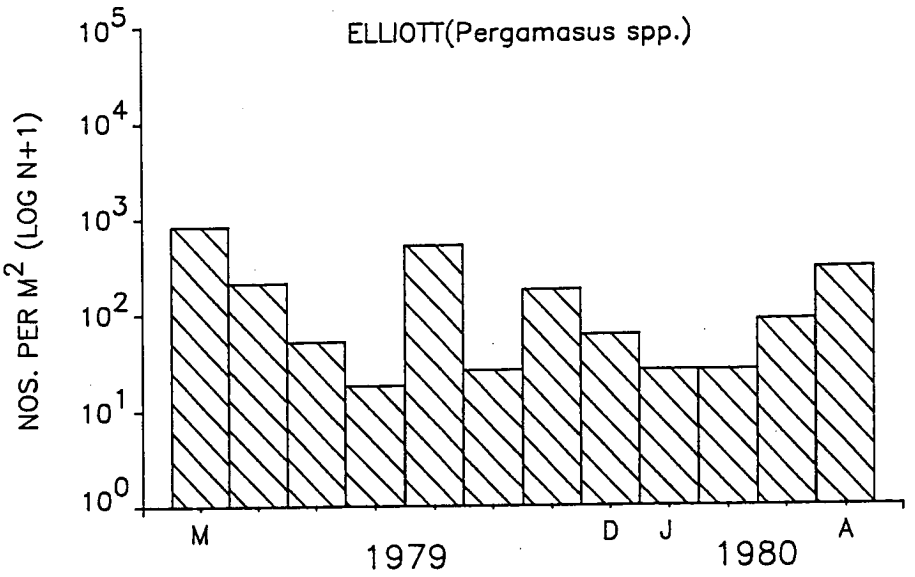

FLOWERDALE(A.baccarum)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
A
1979
D
J
1980
M

Fig. 5.16 Monthly population estimates of Parasitidae at Moriarty 2, Elliott and Flowerdale (1979-80).


MORIARTY2(Pergamasus spp.)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
A
1979
D
J
1980
A


ELLIOTT(Pergamasus spp.)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
1979
D
J
1980
A

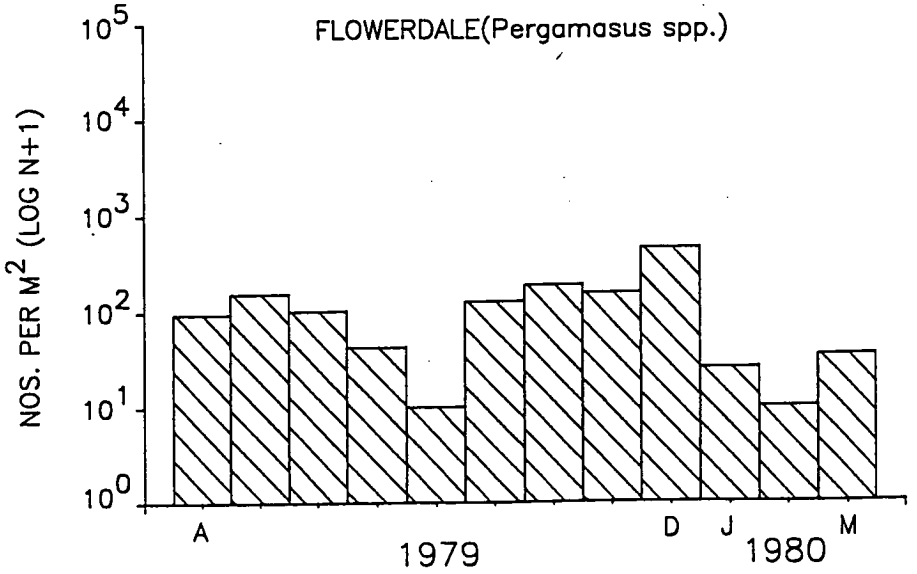

FLOWERDALE(Pergamasus spp.)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
A
1979
D
J
1980
M

Table 5.2 Frequency of occurrence and seasonality of A. baccarum, B. lapidaria, C. latirostris and Pergamasus spp. in low and high rainfall pastures based on survey data.

Species	Season	% High rainfall	% Low rainfall	% Totals
A. baccarum				
	Spring	2.3	6.3	3.3
	Summer	35.3	9.5	25.5
	Autumn	11.1	21.4	13.0
	Winter	0	0	0
	Totals	13.3	6.7	10.9
	X_2^1 (high/low) = n.s.			
	X_3^1 (seasonal) = 25.01**			
C. latirostris	Spring	15.9	37.5	21.7
	Summer	20.6	52.4	32.7
	Autumn	7.9	57.1	16.9
	Winter	0	36.8	29.8
	Totals	12.7	43.8	24.3
	X_2^1 (high/low) = 28.87**			
	X_3^1 (seasonal) = n.s.			
P(P.) longicornis	Spring	65.9	31.3	56.7
	Summer	32.4	28.6	30.9
	Autumn	60.3	14.3	51.9
	Winter	77.8	5.3	19.1
	Totals	56.7	16.9	41.8
	X_2^1 (high/low) = 38.93**			
	X_3^1 (seasonal) = 22.27**			
P(P.) quisquiliarum	Spring	18.2	6.2	15.0
	Summer	2.9	14.3	1.8
	Autumn	19.0	14.3	18.2
	Winter	0	1.0	6.4
	Totals	14.0	10.1	12.6
	X_2^1 (high/low) n.s.			
	X_3^1 (seasonal) n.s.			

Significance levels X_2^1, 5% = 3.84 X_3^1, 5% = 7.81
X_2^1, 1% = 6.63 X_3^1, 1% = 11.3

DISCUSSION

A previous survey by Wallace and Mahon (1972) did not locate C. latirostris in far north-west Tasmania and factors restricting populations in this area are probably similar to those discussed for B. lapidaria in Chapter 3.

According to Wallace (1974a) C. latirostris is a cosmopolitan species found mostly in grassy situations in Europe and known to feed on a range of collembolan species ,however, it appears to have an affinity for oribatid mites. Because of its restricted distribution in high rainfall areas where S. viridis is a major problem and its preference for alternative prey, it is not regarded as having any significance as a predator of this or other collembolan species.

The Australian distribution of Bdellodes affinis, B. currax, B. hadroseta, B. harpax, B. tasmaniensis and B. meridionalis was discussed by Wallace and Mahon (1976) following collections from southern and north-western Australia in 1962 and 1966 respectively. Their results suggest that only B. tasmaniensis is probably confined to Tasmania and although B. meridionalis is common in Europe and North Africa the species is rare in Australia, the only previous collections to those recorded here being a few coastal sites in south-west Western Australia. Further, the results here show that Bdellodes spp. other than B. lapidaria are generally less common in improved pastures. Although Collembola may be their main source of prey, there is no indication they play a major role in the S. viridis predator complex.

Members of the genus Pergamasus are regarded as being amongst the most important acarine predators in palearctic soils feeding on a variety of prey including Collembola (Bhattacharyya 1963). P. longicornis is a cosmopolitan species usually recorded from open or disturbed habitats subject to a moist temperate climate (Harris and Usher 1978). It is common is Europe but has also been recorded in North and South America. Womersley (1942) recorded P. longicornis from Tasmania and South Australia. P. quisquiliarum has been recorded from both Europe and South Africa and although previously recorded from mainland Australia, the species had not been recorded in Tasmania prior to this survey (Lee pers. comm.).

The high frequency of P. longicornis in the wet pasture ecotype of Tasmania suggests it replaces B. lapidaria as the major predator of Collembola in far north-west regions where the latter is not well established. P. longicornis is probably a more effective predator of Collembola than P. quisquiliarum; apart from being more common in Tasmania, males of the former species are larger which may increase its prey range. Although there was no indication that Parasitidae were having any significant controlling effect on S. viridis populations, the

fact that species were seen feeding on a range of Collembola indicates they have a key role in regulating collembolan populations in pasture.

A. baccarum is a cosmopolitan species known to be widely distributed in horticultural situations in Europe and Australia. Although it was of widespread occurrence in Tasmanian pastures it is considered rare in mainland pasture and as an inhabitant of grazed pasture in Europe (Wallace 1981). The results here show that populations in pasture approach their maximum during summer. Therefore, the seasonality of A. baccarum can be considered as a major factor preventing the species from being of any significance as a control agent for S. viridis, whose periods of peak activity usually occur in autumn and spring. Although populations of both species would overlap in some field situations with some predation expected, there was no indication of any significant impact on S. viridis at monitored sites as numbers of A. baccarum were too low during periods of S. viridis activity.

Another anystid species, A. salicinus (L.), an effective predator of a number of Collembola as well as the blue oat mite, Penthaleus major (Dugès) in Europe, was introduced into Western Australia in 1965, released at 4 sites and became established (Wallace 1981). The expectation was that if it was able to control P. major then it might also exert some measure of control over the red-legged earth mite, Halotydeus destructor (Tucker) as well as S. viridis. Unfortunately, as is also the case with bdellids, anystids are slow to spread. A redistribution programme has now been initiated by the W.A. Dept of Agriculture to enable establishment of this predator in more areas of W.A. and also South Australia (Michael pers. comm.). Although two shipments of ca 1200 and 500 A. salicinus were released in southern Tasmania in 1987 and 1988 respectively there is no evidence of establishment (Ireson unpubl. data). Perhaps the climate range here is unsuitable as Wallace (1981) found the species to be restricted to regions in Europe influenced by the Mediterranean climate. Sites where the species has established in Western Australia are also subject to a Mediterranean-type climate, with mean annual rainfall up to 400 mm (maximum in Winter) and warm dry summers. Sites that are closest to this are in south-eastern Tasmania and have a higher rainfall (ca 600 mm) that is evenly distributed throughout the year. If A. salicinus did establish in Tasmania its main benefit would probably be as a predator of H. destructor rather than S. viridis as the latter species is not considered a major problem in the drier pasture regions of the State (Chapter 3). Concern has also been expressed that because anystids are not discriminating in their diet, any predation on bdellids may cause an increase in numbers of Collembola (including S. viridis) (Michael pers. comm.). However, Wallace (1981) noted that in the pastures of Southern France a predator - prey complex of B. lapidaria, Neomolgus capillatus, P. major, S. viridis and A. salicinus co-existed and no adverse effects were expected to result from the establishment of the latter species in

Australia.
Because of the climatic restraints, it appears unlikely at this stage that A. salicinus will establish in the cool, damp regions of Tasmania where S. viridis is a pasture pest. Further, no anystid species are known to inhabit pastures in large numbers in the Brittany region of north-west France (Wallace 1981), the homoclime of north-west Tasmania (see Chapter 6).

A number of generalist non-acarine predators would be expected to exert a degree of population control over the collembolan prey complex in Tasmanian pastures. Non-acarine predators of Collembola are widely documented in the literature by a number of authors, including Holdaway 1927; MacLagan 1932a, Paclt 1956; Choudhuri 1962; Christiansen 1964, 1971; Ernsting and Joosse 1974; Manley et al 1976; Ernsting et al 1977; Johnson and Wellington 1980; Thiele 1987; de Ruiter et al 1988; Gatland 1988.

In Tasmanian pastures, McQuillan and Ireson (1981) record a number of possible predators of Collembola including spiders from the family Lycosidae as well as beetles from the familites Carabidae, Anthicidae and Staphylinidae. Additional collections from pasture have revealed a large staphylinid fauna with 14 genera from 7 sub-families being identified during recent surveys; a number of unidentified spider species have also been collected (Ireson unpubl. data). In New Zealand, Gatland (1988) observed 8 species of spider attacking S. viridis but none were able to exert any significant control over populations.

The use of generalist predators which are able to maintain themselves on other prey species during periods when their main prey species are in low numbers was discussed in Chapter 3 in relation to B lapidaria, however, it is not known if any non-acarine predators in Tasmanian pastures have Collembola as their primary source of prey as most appear to be polyphagous. In addition, there is no evidence that the predatory activities of any species are restricted to S. viridis.

Huffaker et al (1976) point out that natural enemies may impose limits on the extent of pest population fluctuations, but for biological control to occur the prey must have evolved specific morphological, physiological and behavioral adaptations to its prey. The fact that severe infestations of S. viridis continue to occur in Tasmanian pastures indicates that the naturally occurring predators in the established complex are unable to effectively reduce the number and frequency of severe infestations that occurs annually during autumn and spring. Van Emden (1982) stated that if effective natural enemies were sparse in a given ecosystem, then a vital component in an integrated pest management programme was lacking and that it may be worthwhile investigating the introduction of new predators. At this stage, the best available predator for introducing into Tasmania appears to be the

spiny snout mite, Neomolgus capillatus which has been observed feeding on S. viridis in many European pastures (Wallace 1974a). Perhaps this species will, if integrated into the S. viridis predator complex, alter the balance to a stage where control of S. viridis by natural predation is achieved, hopefully without having to consider the introduction of additional predators.

CHAPTER 6

BIOLOGICAL CONTROL OF *SMINTHURUS VIRIDIS* (L.) IN FAR NORTH-WEST TASMANIA WITH THE INTRODUCTION AND ESTABLISHMENT OF A EUROPEAN PREDATOR, THE SPINY SNOUT MITE, *NEOMOLGUS CAPILLATUS* (KRAMER)

INTRODUCTION

The lucerne flea, Sminthurus viridis (L.) is regarded as a significant pest in Tasmanian pastures in the dairying areas of the north-east (Winnaleah district) and the north-west. In this latter region, it is particularly severe in the Smithton district to the west of Rocky Cape. Furthermore, the latest figures from chemical retailers show that the use of insecticides to control the pest is widespread. In 1987/88, 15000 ha of pasture were sprayed in the Smithton district alone. This represents 29% of the total area of improved pasture in the region. The studies on the distribution and population dynamics of Collembola and their predatory mites (Chapters 3, 4 and 5) showed that:

(i) The pasture snout mite, Bdellodes lapidaria (Kramer), regarded in mainland pastures as the most important predator of S. viridis (Wallace 1967) appeared to thrive best in drier areas of Tasmania where the mean annual rainfall is <800 mm (Midlands, east and south east).

(ii) In these areas, S. viridis is not numerous and collembolan species other than S. viridis are the main food source.

(iii) In north-western Tasmania where S. viridis is well established, the distribution limits for B. lapidaria did not correspond to those defined by Wallace and Mahon (1971).

(iv) The mite was found to be rare in the Smithton district around the 1200 mm annual isohyet where there was less seasonal fluctuation in temperature compared to the rest of the State.

(v) At monitored north-west sites where B. lapidaria was established, no significant predator-prey relationship was found to exist between this and other known predators (Parasitidae) and S. viridis. Although the problem appeared to be greater in areas where B. lapidaria was completely absent, damaging populations up to 50,000/m^2 were still recorded in pastures where B. lapidaria was active.

(vi) There were no other established predators capable of exerting significant control over S. viridis populations in high rainfall pastures.

Obviously, there is a requirement for the establishment of a suitable predator of S. viridis that is pre-adapted to the climate of north-west Tasmania.

In Western Australia, Wallace (1967) found that B. lapidaria did not occur over the whole area infested by S. viridis. Populations of S. viridis were well established in drier northern regions and not affected by B. lapidaria predation. Consequently, predators associated with S. viridis in the Mediterranean region of Europe were investigated to determine if any species would be suitable for the drier areas of Western Australia outside the range of B. lapidaria. European surveys by Wallace during 1964-65 (Wallace 1974a, 1974b) showed that the spiny snout mite, Neomolgus capillatus (Kramer) (Fig. 6.1) was an abundant species mainly

received from Western Australia, following the collection of small numbers by the Western Australian Department of Agriculture from one of the early release sites established by Wallace in 1969 (Wallace 1974a). A second consignment was received from Montpellier in southern France following collections there by CSIRO in February 1982.

DETAILS OF N. CAPILLATUS INTRODUCTIONS TO TASMANIA, 1981-82

(i) Introduction from Western Australia

One consignment of 50 mites was forwarded in July 1981. No further consignment was received as attempts to collect the predator from other sites were unsuccessful (Moulden, pers. comm.).

Consignment details are summarised as follows:-
Source: Waddi Forest
Date of Receipt: 16.7.1981
Method of Shipment: 20 x 2.5 cm pyrex test tube plugged with moist facial tissue.
Survival in Transit: 80%
Quarantine Procedures: None necessary.

The method of shipment used would have been inadequate over longer distances since the mites require reasonable ventilation with moist, but not wet conditions. In this instance, most of the mortality was due to specimens becoming trapped in condensed moisture on the walls of the tube.

In view of the small number of N. capillatus received and the unlikelihood of further consignments becoming available from Western Australia, it was decided to retain these specimens in the laboratory to develop an expertise in culturing and handling techniques. Such preliminary investigations were considered important since, in any shipments of adult N. capillatus from Europe, Commonwealth quarantine procedures at the time specified that only the eggs, F1 or subsequent laboratory generations could be released in the field.

(ii) Introduction from Montpellier

A single consignment of 150 mites was forwarded in February 1982 by CSIRO.

Consignment details are as follows:-
Source: Montpellier
Date of receipt: 22.2.1982
Method of Shipment: Essentially as described by Wallace and Walters (1974). The shipment cages consisted of plastic sample tubes 6.5 cm long and 2.5 cm in diameter. At one end a piece of cellophane had been placed over a cap containing water before being pressed into place. At the other end a piece of tissue was placed over a perforated cap prior to insertion. The cage thus had a moist end and a well-aerated dry end.

Survival rate in transit: 43% (this compared to a mean survival rate of 60% for B. lapidaria shipments from Western Australia to South Africa (Wallace and Walters, 1974)).

Quarantine procedures: Although there was some delay in flight schedules and quarantine clearances, the consignment was transferred on arrival to the quarantine room at New Town Research Laboratories. The packing material was sealed in plastic bags and burnt while dead mites in the consignment were retained in 90% alcohol for the museum collection. The remaining live mites were retained in culture under quarantine and the eggs produced (Fig. 6.3) together the those laid in transit, were held for later field release.

CULTURING OF N. CAPILLATUS

(i) Previous work

Currie (1934) found that laboratory cultures of B. lapidaria when supplied with food at ordinary winter temperature in Perth (ca 18°C) lived only for about 9 days.

The difficulties in culturing N. capillatus in the laboratory were also made evident from studies by Wallace (1971, 1974a) who concluded that maintaining and breeding large numbers of bdellid mites in the laboratory was a lengthy process generally unlikely to succeed.

Wallace (1971) demonstrated that B. lapidaria always laid eggs which were in varying stages of diapause, with incubation periods at 16°C ranging from 4 to 30 weeks. Development proceeded in eggs under dry and moist conditions at constant temperatures ranging from 16 to 38°C, but most rapidly at 30°C, at which 4-8 weeks exposure was sufficient to ensure that a high proportion of the eggs hatch within 5 weeks when subsequently moistened at 16°C. Wallace (1971) had also suggested that eggs of N. capillatus behaved similarly and hatched over a prolonged period at 16°C with a mean incubation period of 170 days (range 24 to 298). The preliminary culturing and incubation studies on the Western Australian shipment of N. capillatus was undertaken using the egg incubation studies on B. lapidaria by Wallace (1971) as a guideline.

(ii) Laboratory culturing methods for Western Australian shipment

The 40 live N. capillatus adults received were divided amongst three plastic containers 6.5 cm high and 10.5 cm in diameter with plastic clip-on lids. A 6-8 diameter hole had been bored into each lid and covered by a terylene gauze to facilitate air circulation. A piece of filter paper was used to line the base of the containers onto which was placed 4-5 saturated wads of facial tissue to provide moisture and oviposition sites for the mites. Live sminthurid and entomobryid Collembola were collected, sorted and added to the containers every 1-2 days to provide a food source of the mites.

The cultures were placed in a 'Conviron' controlled environment cabinet (model E77H) set at 12°C and a photoperiod of 10 hours. The maximum relative humidity obtainable was 95%, however, the saturated wads of facial tissue in the culture containers probably enabled the humidity within to fluctuate nearer saturation level.

A cabinet temperature of 12°C was chosen to approximate average field temperatures in Tasmania in autumn and spring months when bdellids are active.

The containers were examined daily:

(a) To check the viability of the culture
(b) To replenish collembolan food supply when necessary
(c) To remove and examine tissue "oviposition sites" for eggs and replace them with freshly moistened wads

Any dead mites in the culture were removed and retained in 90% alcohol or mounted to check identifications; all specimens were retained in the museum collection.

In most cases eggs were laid on the tissue wad "oviposition sites" and only occasionally had to be removed directly from the filter paper lining. The wads were usually only slightly damp after 24 hours and would have needed re-moistening had they not been removed. All wads removed from the containers were examined for eggs under a compound microscope. Any eggs laid were separated from the wads using two pairs of fine forceps to remove the strands of tissue to which eggs (or groups of eggs) were attached. This avoided direct contact and therefore possible damage to the eggs.

All eggs removed were counted and placed on clean filter paper in glass petri dishes. They were then subjected to a constant temperature of 24°C under air dry conditions (ca 60% RH) for 8 weeks for diapause development and then incubated at 16°C with free water contact (100% RH) to bring them eclosion.

(iii) Laboratory culturing methods for Montpellier shipment

The methods used were the same as those described for the Western Australian shipment, although the mites were held in a 'Fisons' controlled environment cabinet (Model 600G3/THTL) under quarantine. All eggs were incubated at 30°C for 5 weeks to bring them as close to hatching as possible, prior to field release in April 1982.

RESULTS

(i) Egg cultures

	W.A. Shipment	Montpellier Shipment
No. of eggs laid in transit	13	287
% eggs laid in transit	3.8	70.0
No. of eggs laid in culture	329	125
% eggs laid in culture	96.1	30.0
Total number of eggs laid	342	412
% culture mortality after 7 days (adults and nymphs)	50	71
% culture mortality after 14 days (adults and nymphs)	93	90.8
Mean estimated no. of eggs/female* in transit	0.5	3.8
Mean estimated no. of eggs/female* in culture	16.5	3.8
Mean estimated no. of eggs/female* overall	13.7	5.6
Culture longevity (days to which last mite died	36 (last mite was ♀**)	23 (last mite was ♂)

* assuming sex ratio of 1:1

** only one N. capillatus remained alive after 16 days and it survived a further 36 days; during this time it laid 125 eggs, ca 3.7% of the total for the shipment.

(ii) Diapause development culture (Western Australian shipment only)

Following the 8 week exposure to 24°C, about 75% of the eggs reached eclosion in a further 8-10 weeks after transfer to free moisture at 16°C. However, many of the N. capillatus died at eclosion in a partially emerged state, while others died soon after emergence and no hatchling nymphs survived for more than 24 hours.

Humidity was probably one of the most critical factors which affected survival. Emerged nymphs were observed to be totally immobilised by even small droplets of free moisture. Alternatively, if humidity dropped too far below saturation, the nymphs succumbed rapidly to the "dry" conditions.

DISCUSSION

Most N. capillatus from both shipments died in culture within a fortnight which illustrates that soft bodied bdellids do not generally live for long periods in the laboratory and confirms statements by Currie (1934) and Wallace (1974a).

Field longevity and fecundity of individual bdellid mites are unknown and it would be difficult to assess just how much this may have been affected by collection, shipping and culture conditions. Many of the N. capillatus specimens received were adults and had probably already lived most of their natural life span and deposited a portion of their eggs in the field before capture. Microscopic examination of some specimens,

however, showed that some died in culture without depositing their full complement of eggs, with estimates of the numbers of eggs remaining in the bodies of some females ranging from 50-70. The fact that one specimen from Western Australia survived 36 days in the culture and laid 126 eggs suggests that the culture conditions used could allow specimens to survive long enough to enable significant oviposition. It appears that during long transits, significant oviposition may take place during shipment and that sub-optimal conditions experienced by mites in transit cages may even act as a stimulus to oviposition.

Although the culture observations demonstrated that N. capillatus adults can be kept alive in the laboratory to produce eggs for field release, the egg incubation studies emphasised the difficulties in attempting to rear the mite successfully through one complete generation so that a first generation of egg-laying laboratory bred adults could be used for field release.

Apart from difficulties in avoiding excessive mortality once eclosion had taken place, the whole process was indeed lengthy and required a high labour input, particularly if large numbers of mites were involved.

At the time this work was carried out, Commonwealth quarantine regulations prohibited active N. capillatus stages imported from Europe being released directly into the field unless bred through one generation. The studies therefore confirmed that the best alternative method of field establishment would be the release of eggs laid in transit and in the laboratory, providing sufficient numbers of adults were available to produce an adequate number of eggs. The procedure would then be to incubate the eggs until they were close to hatching and release them in the field during autumn or spring, so that they could continue their development to eclosion within a few weeks. This would overcome prolonged initial exposure of eggs in the field where they would be protected only by artificial means and probably more vulnerable to predation than if oviposition had occurred in situ.

Quarantine procedures did not restrict adult releases of either B. lapidaria in South Africa (1963-1966) or N. capillatus in Western Australia (1969) and adults were released directly into the field (Wallace and Walters 1974; Wallace 1974a). However, Wallace (op. cit.) was able to show that field establishment of N. capillatus from egg releases was possible following significant recoveries of the predator from Waddi Forest (Western Australia) during 1971, after 16,000 eggs laid in transit from Morocco and Montpellier had been released there in 1969-70.

The 150 N. capillatus collected at Montpellier and forwarded to Tasmania were insignificant in comparison to numbers used to successfully establish B. lapidaria in South Africa (Wallace and Walters 1974) and N.

capillatus in Western Australia (Wallace 1974a). South African consignments from 1963 to 1966 transported 78,210 mites in 13 shipments (mean no. per shipment = 6,016) which laid a total of 30,000 eggs in transit (ca 1.3 eggs/female) and in 1969 11 shipments of N. capillatus from Morocco and southern France totalled 17,500 (mean no. per shipment 1,591) which produced 16,000 eggs in transit (ca 1.8 eggs/female). It were therefore obvious that any serious attempt to introduce and establish N. capillatus in Tasmania would need to involve collections of a similar magnitude. It was concluded that future consignments of only a few hundred N. capillatus from either Montpellier or Western Australia was a questionable use of resources, mainly because of the amount of labour involved in collection, shipping and culturing of mites and then releasing the relatively small number of eggs they would produce, which would probably be inadequate to enable field establishment as was the case with the Montpellier shipments. Additionally, these strains of N. capillatus were imported from localities which varied considerably in climate from that experienced in north-west Tasmania.

INTRODUCTION OF N. CAPILLATUS FROM EUROPE 1985-1988

In 1981 the Commonwealth Institute of Biological Control (CIBC) based at Delémont, Switzerland, offered to undertake collections of N. capillatus for consignment to Tasmania if provided with the appropriate technical information (Carl pers. comm.). This was followed by a visit to CIBC, Delémont, by Ireson in October 1983, to instruct staff on the identification of N. capillatus and the methods that could be used for field collection and consignment to Tasmania. N. capillatus was well established in pastures around Delémont. It was therefore proposed that initial collection attempts by CIBC be carried out in this region followed by collections from the Brittany region of France. Initial collections at Delémont were regarded mainly as a cost saving device over a period when collection and consignment techniques were being refined. However, as indicated in Table 6.1, Delémont was not as close a climate match with sites in north-west Tasmania as was Brest, which was representative of sites in the Brittany area. Although the data for Delémont show that long term means for autumn, spring and annual rainfall approximated records for north-west Tasmania, maximum rainfall at Delémont is in summer as compared to the winter maximum in north-west Tasmania. Additionally, although summer temperatures were closely matched, the mean temperatures for autumn, spring and particularly winter were much lower for Delémont. However, it was considered possible that a cold-adapted strain could survive milder winters in Tasmania.

Although the first collections were scheduled for the spring of 1984 (European autumn), they were delayed until late autumn 1985 (late spring in Europe) due to unfavourable weather conditions around Delémont. By this time, Commonwealth quarantine regulations for N. capillatus introductions had been revised to allow release of imported active stages directly into the field, thus eliminating the necessity for labour

Table 6.1 Comparison of long term figures for temperature and rainfall at Delémont and Brest with Smithton and East Devonport.

Site	Parameter	Summer	Autumn	Winter	Spring	Mean
Delémont*	Mean T°C	16.0	8.0	0.3	7.8	8.0
	Rainfall (mm)	321	244	189	251	1005
Brest**	Mean T°C	16.1	11.1	8.5	12.6	12.1
	Rainfall (mm)	150	260	270	162	842
Smithton	Mean T°C	15.8	13.3	9.2	11.8	12.5
	Rainfall (mm)	168	258	388	288	1102
Devonport	Mean T°C	16.2	13.1	8.7	8.2	11.6
	Rainfall (mm)	163	232	311	218	924

* Figures supplied by CIBC

** Figures obtained from Walter et al. (1975)

intensive culturing procedures. The success of establishment was also enhanced by enabling imported N. capillatus to oviposit directly in the field, thus avoiding artificial placement of eggs. Direct release of N. capillatus without quarantine was not considered to present an environmental risk for Tasmania because European pastures were known to contain a complex of pest species and predators already present in Australia. In addition, Wallace (1974a) had set a precedent 15 years earlier by introducing the predator into Western Australia with no apparent problems.

METHODS

(i) Collection and sorting of N. capillatus

Collections in Europe were carried out during the European autumn and spring when population monitoring in pastures around Delèmont showed numbers to be at (or approaching) maximum levels (Affolter pers. comm.).

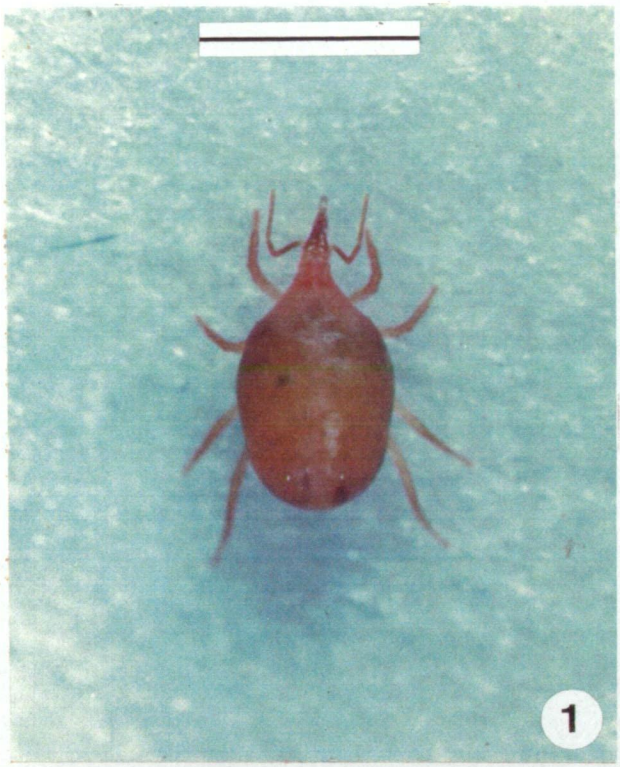
All 1985 collections were from the Delèmont area with subsequent collections (1986-1988) from Brittany (Table 6.2). Surveys and collections were carried out using the suction apparatus. Using this technique it was found that mass collections were feasible from pastures with a minimum mite population of $20/m^2$. Following the location of suitably large populations, sample contents were tipped onto sorting trays and individual mites sucked into tubes. All collections were subsequently returned to the laboratory for further sorting (to remove unwanted insects, mites and any plant debris), identification and packaging.

(ii) Consignment

The type of shipment cage used consisted of a small glass tube 10.0 cm long and 2.0 cm in diameter. At one end a plastic cap containing a moist cotton wool plug was fitted and covered by a piece of gauze. At the other, a piece of gauze was held in place by a perforated cap. This provided the cage with a moist end and an aerated dry end. The gauze provided an oviposition site for the mites and an additional oviposition site was provided by a narrow strip of filter paper (8.5cm x 1.5 cm) placed inside each tube (Fig. 6.4).

Most of the mortality during shipment was attributed to mites becoming engulfed in condensed moisture droplets on the sides of the glass tubes. An additional refinement was found to reduce this mortality up to 28%. This consisted of a gauze sleeve placed inside the cage which increased the surface area within the cages and absorbed moisture, thus reducing condensation levels and contact of mites with the sides of the tube; it also provided additional oviposition sites (Fig. 6.4). Up to 500 mites were placed in each cage and up to eight cages were carefully packed into aerated plastic containers (diameter 11.0 cm; height 15.0 cm) containing tissue pads. Up to three plastic containers were packed into an internally padded cardboard box (30 cm^3) for air freighting to Tasmania.

Figs 6.1-6.4 Neomolgus capillatus (Kramer): (1) adult N. capillatus (live specimen); (2) N. capillatus attacking S. viridis; (3) eggs of N. capillatus; (4) cages (with and without gauge sleeves) used to import N. capillatus from Europe. Scale lines 1 mm Figs 6.1, 6.2; scale line 2.6 mm Fig 3.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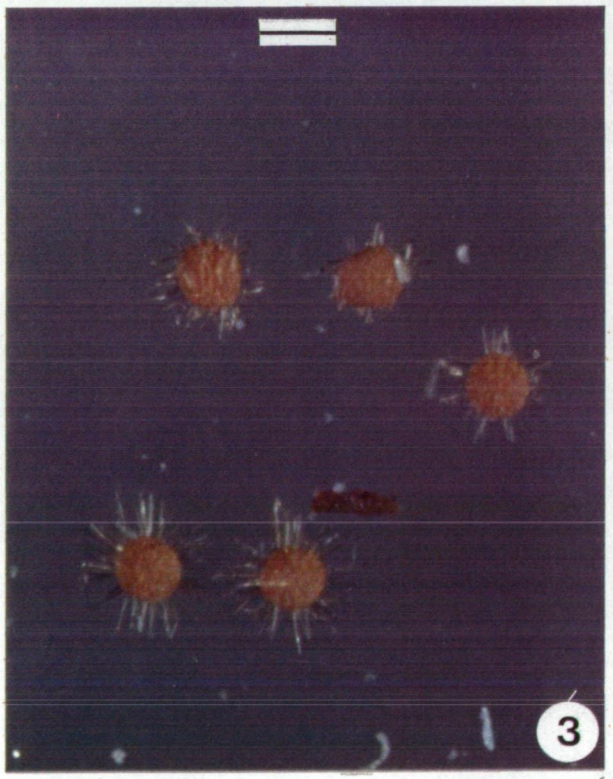
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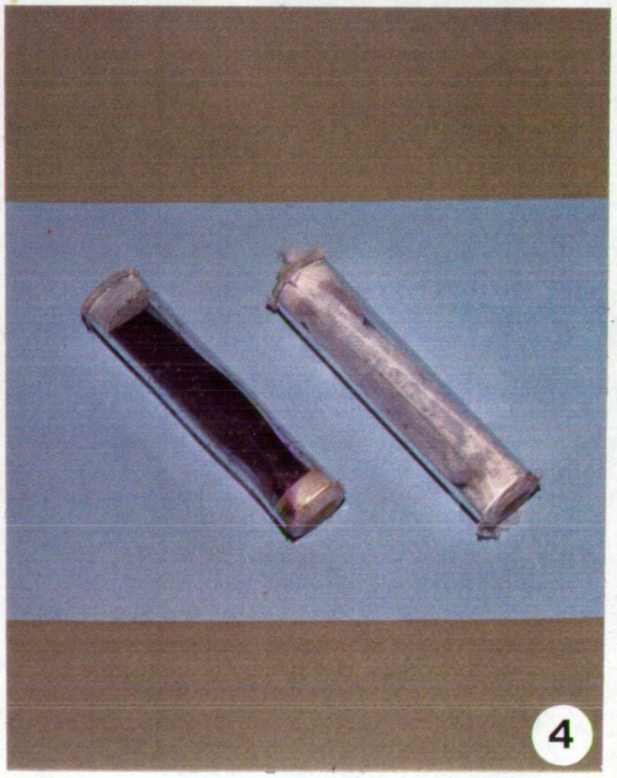
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Between June 1985 and October 1988, 34,515 N. capillatus were consigned to Tasmania for field release with the shipment methods enabling a mean survival rate of ca 79% (Table 6.2). This survival rate compares favourably with the level of 60% achieved by Wallace and Walters (1974).

(iii) Releases of N. capillatus in Tasmania

Since prolonged captivity would obviously cause substantial increases in the mortality of the introduced mites, releases were carried out within 48 hours of the arrival of the consignment. This followed rapid clearance of consignments, by prior arrangement with customs and quarantine officials. Releases were made in improved pastures at 5 sites, 4 in the north-west of Tasmania and one in the south of the State (Table 2). The southern site, Lachlan, was chosen as a back-up to the north-western sites because it experienced a similar climate and had been used to successfully establish a French strain of ragwort flea beetle, Longitarsus flavicornis (Stephens) introduced for the biological control of ragwort in 1979 (Ireson and Terauds 1982). All north-west release sites carried high populations of S. viridis at the time of release and although S. viridis was absent from Lachlan, other Collembola were active there.

At the release sites, mites were emptied from the cages into a sorting tray. Dead mites were returned for mortality estimates and live mites released at a fixed point. Eggs were counted then released by placing them in sheltered positions under pieces of bark at the release point, a method used by Wallace and Walters (1974). All release sites were left unfenced.

(iv) Establishment assessments

Sites at which initial releases were carried out in autumn were assessed the following spring (and vice versa) by suction sampling the central release point. Sampling at Delémont suggested that N. capillatus passes through at least 4 generations per year in Europe, therefore it was assumed that if no recoveries were made at Tasmanian release sites 12 months after the initial release, then the population had not survived.

RESULTS

Results of establishment assessments are summarised in Table 6.2. The most recent assessments (June 1989) showed that after four years, only small numbers ($< 1/m^2$) of the imported Swiss strain of N. capillatus were active at the Moriarty site (but only at the central release point) and no establishment of this strain occurred at Irishtown (Site 1). However, significant field recoveries of the French strain of N. capillatus have been made at both Irishtown (Site 2) and at Lachlan. Populations have now become permanently established at both these sites, with recoveries of large numbers of the predators being made 2 and 3 years respectively after initial releases. Current estimates suggest that Neomolgus has spread over ca 500 m^2 at Lachlan (maximum population at central release

Table 6.2 Details of consignments of N. capillatus from Europe to Tasmania (1985-1988), together with a summary of establishment surveys.

Shipment No.	Origin	Date received	No. Mite predators	Eggs laid in transit	No. Live predators released	% mortality in transit	% survival	Date released	Locality released	Establishment rating
1	Delémont, Switzerland	01.06.85	3,603	114	2,816	22.0	78.0	02.06.85	Moriarty	B
2	La joux, Switzerland	08.06.85	11,468	782	9,788	14.7	85.3	09.06.85	Moriarty	B
3	La joux, Switzerland	24.09.85	4,900	106	3,114	36.4	63.6	25.09.85	Irishtown (Site 1)	C
4	St. Malo, France	04.10.85	3,545	94	3,280	7.5	92.5	05.10.85	Irishtown (Site 2)	A
5	Dol-de Bretagne, France	25.05.86	1,588	3,208	1,390	13.2	86.8	26.05.86	Lachlan	A
6	Dol-de Bretagne, France	20.09.86	4,811	141	3,489	27.5	72.5	20.09.86	Lachlan	A
7	Bernay (Normandie), France	02.06.87	1,440	116	1,137	21.0	79.0	02.06.87	Irishtown (Site 2)	A
8	Landepereuse (Eure), France	10.10.88	3,160	110	2,212	30.0	70.0	11.10.88	Irishtown (Site 3)	B

* Key to establishment ratings

A - Definitely established, with significant numbers spreading outside the release area

B - Recoveries of small numbers from release site but establisment uncertain.

C - Check made but no recoveries indicating failure to establish.

point recorded at 100/m^2 in December 1988) and over ca 1 ha at Irishtown (maximum population at central release point recorded at 100/m^2 in May 1988).

DISCUSSION

Although the apparent failure of the Swiss strain of N. capillatus to establish at Irishtown (Site 1) and the low numbers recovered at Moriarty (four years after release) could be explained on the basis of climatic incompatabilities, other factors may also have been involved. For instance, poor viability of the population and its low fecundity at the time of release may have been the cause of the establishment failure at Irishtown (Site 1). Although S. viridis was absent at the Lachlan site this was obviously not a limiting factor as the predator was able to survive on other collembolan species including the introduced sminthurids, Bourletiella viridescens, Sminthurinus elegans, and native Katianna spp., the introduced entomobryid, Entomobrya multifasciata and the isotomid, Isotomurus palustris all of which are known sources of alternative prey for B. lapidaria (Chapter 4). Wallace and Walters (1974) also discuss the establishment of B. lapidaria at a site in South Africa where entomobryid and sminthurid Collembola other than S. viridis were the main food sources for the predator.

As European importations are expected to terminate by October 1989, future Tasmanian work will involve gauging the effectiveness of N. capillatus as a predator of S. viridis by quantitative analysis of both predator and prey populations. Collection and transfer of established populations to new sites will be necessary to facilitate the rate of spread as natural dissemination of newly established pasture bdellids is slow.

In Western Australia, the estimated maximum area of spread over the 10 year period from the time of release in 1969 until 1979 was ca 10 ha. However, populations may have been somewhat restricted by drought (Wallace pers. comm.). The most recent surveys carried out in August 1988 showed that N. capillatus could be found 1.5 km from its original release point and it was now estimated that the predator had probably established over ca 100 ha (Michael, pers. comm.). In South Africa, Wallace and Walters (1974) report that populations of B. lapidaria had spread over a maximum of 15 ha, 4 years after their initial release. Obviously, rates of spread would be expected to differ considerably because of the range of variables that could affect populations at each particular site, such as prevailing weather conditions and grazing strategies.

The scale of any dissemination programme for N. capillatus in Tasmania will ultimately depend on the predatory effectiveness of N. capillatus. It may be more effective as a synergistic predator in combination with B. lapidaria in north-west pastures where the latter species is well

established. Alternatively, at far north-west sites where B. lapidaria is less common it may be possible for N. capillatus to build-up in larger numbers due to the abundant food source. However, predation of S. viridis by N. capillatus in Tasmania may also be affected by the abundance of alternative collembolan prey and the proportion of S. viridis nymphs available at any given time. As discussed in Chapter 3, the cool wet climate of the north-west and the frequently indefinite autumn breaks result in staggered hatching of S. viridis, so that a considerable range of stages from young nymphs to adults may exist in any population, a high proportion of which may be beyond the predatory range of N. capillatus. In areas where a precise autumn break after a lengthy summer drought ensure a sychronised hatch, the entire S. viridis population at this time would be expected to consist mainly of small nymphs susceptible to predation. This situation is atypical for Tasmania but has been observed at north-west sites after an exceptionally dry summer (Ireson and Leighton 1986). It is typical of areas with a predominantly Mediterranean climate such as south-west Western Australia. Here, Wallace (1981) reported that monitored S. viridis populations were 22% lower in a plot where N. capillatus (southern Europe strain) was present, compared to a nearby control area indicating that this predator does have the ability to effectively reduce S. viridis populations. Wallace (op. cit.) also considered that even small reductions in numbers as a result of predation may be sufficient to render S. viridis unimportant on many properties that currently used sprays to control populations. Furthermore, Wallace and Mahon (1963) had stated that the importance of S. viridis may have been exaggerated in the past because many infested pastures in Australia were often understocked.
Although up to 15,000 ha of improved pasture are treated annually for control of S. viridis in the far north-west of Tasmania, the actual damage in terms of lost production is still to be quantified. Many Tasmanian dairy producers maintain there is a noticeable drop in milk production from cattle grazed on S. viridis infested pasture, compared with herds grazed on uninfested pasture. How much of this is actually due to a reduction in clover leaf area is currently being investigated. It is possible that S. viridis activity resulting in the fouling of pasture rather than loss of leaf area may often be the significant factor in production losses.

Preliminary studies by Ireson and Leighton (1986) showed that sweep net numbers of up to 300 S. viridis per 6 m sweep were not enough to cause any significant damage to white clover (T. repens) in north-west Tasmania. Work in New Zealand has shown that economically important damage occurs only when large areas of leaf are lost, and although much of the damage that does occur looks dramatic, it is often fairly superficial and of little consequence. In addition, white clover has a tremendous ability to regrow after brief periods (1-2 weeks) of heavy damage (Wrenn pers. comm. Even so, Pottinger et al (1985) were able to show that pasture production losses in New Zealand of 18 and 30% did

occur over 6 week intervals when catches of 500-800 S. viridis have been taken per 6 m of pasture swept. In these cases increases in pasture production over the period were found to be worth 7 times the cost of treatment, although it is unusual for S. viridis to maintain high numbers for long periods of time as was recorded here; populations usually fluctuate markedly.

Strip grazing dairy cattle is an effective management practice for significantly reducing S. viridis populations (Pottinger et al., 1985; Ireson and Leighton, 1986). However, the practice is labour intensive and not yet in regular use on Tasmanian dairy farms. Control using pesticides, therefore, will probably remain the most widely used remedy in the short term. Furthermore, because of the extended period of activity of S. viridis (and other Collembola) in Tasmanian pastures (compared to mainland pastures) (see Chapter 8), the frequent absence of a distinct autumn break resulting in staggered hatching, coupled with the abundance of alternative prey species, significant control of S. viridis by the addition of N. capillatus to this ecosystem may prove too difficult for one predatory species to accomplish. If this is so, then in the absence of other suitable predators, perhaps other potential bio-control agents such as entomogenous nematodes or fungal pathogens may prove, individually, to be more effective bio-control agents in the long term.

CHAPTER 7

A LABORATORY STUDY TO ASSESS THE POSSIBLE USE OF PARASITIC NEMATODES FOR THE CONTROL OF SMINTHURUS VIRIDIS (L.)

INTRODUCTION

Biological control of pests through the use of parasitic nematodes offers a promising alternative to the over-reliance on pesticides (Gordon and Webster 1974). Edwards and Oswald (1981) observed significant decreases in populations of the euedaphic collembolan Onychiurus armatus (Tull.), following applications of Neoaplectana carpocapsae Weiser. Although Poinar (1979) listed 250 insect species from 10 orders as being susceptible to N. carpocapsae, there were no records of nematode parasitism of surface-active Collembola. To test the feasibility of using parasitic nematodes as an alternative to predatory mites for the biological control of S. viridis, a laboratory study to assess the susceptibility of S. viridis to parasitism by the entomogenous nematodes Steinernema bibionis (Bovien) and Heterorhabditis heliothidis (Kahn et al.) was carried out. The results are presented in this Chapter.

MATERIALS AND METHODS

Cultures of 20 field collected S. viridis, mostly 5th-9th instar, were established in each of 30 plastic containers (6.5 cm high x 10 cm diameter). Seedling oil poppies (Papaver somniferum) at the cotyledon and 1-2 leaf stage were supplied as a food source and replaced as required. A filter paper lining and tissue wads were used to maintain moisture in the cultures and dampened daily with Hoaglands solution.

The cultures were sprayed with 5 ml of water containing 20,000 infective juvenile S. bibionis or H. heliothidis while controls were sprayed with 5 ml of water only. There were 10 replicates of each treatment. Immediately after spraying, the cultures were placed in a 'Fisons' controlled environment cabinet (Model 600G3/THTL) at 12°C and ca 90% relative humidity.

Cultures were examined daily from 2 days after spraying and dead specimens were dissected to record the number of nematodes present. After 8 days all surviving specimens in 5 of the cultures from each treatment were dissected and examined for parasitism. The remaining 5 cultures in each treatment were examined daily for a further 5 days before dissection of the surviving S. viridis.

RESULTS AND DISCUSSION

This study is the first record of infection of an epigaeic species of Collembola by steinernematid and heterorhabditid nematodes. The mean number of infective stage nematodes recorded in each parasitised S. viridis was 12.1 (range 1-43) in H. heliothidis treatments and 22.1 (range 1-120) in S. bibionis treatments.

Table 7.1 shows that S. bibionis and H. heliothidis application significantly ($P<0.05$) increased mortality of S. viridis after 8 days. After 14 days there were also significant increases in mortality in both S. bibionis ($P<0.05$) and H. heliothidis ($P<0.10$) cultures. Dissection of

Table 7.1 Mortality of Sminthurus viridis (L.) after exposure to the entomogenous nematodes, Steinernema bibionis and Heterorhabditis heliothidis in laboratory cultures.

Treatment	Mean % mortality of S. viridis	
	8 days post spray	14 days post spray
Untreated	18.4	58.4
H. heliothidis	51.7	81.4
S. bibionis	64.0	88.1
lsd 10%	23.5	20.3
lsd 5%	28.8	24.9

the surviving S. viridis revealed that after 8 days 34.6% were already parasitised in S. bibionis treated cultures and 35.3% in H. heliothidis treated cultures. At the 14 day examination no surviving S. viridis were parasitised in the H. heliothidis treated cultures, however, 44.4% were parasitised in cultures treated with S. bibionis. The inevitable death of parasitised S. viridis would increase mortality in the S. bibionis treated cultures of 90.2%.

The increase in natural mortality of S. viridis in control cultures from day 8 to day 14 (Table 8.1) suggests that deterioration of culture conditions may have affected their survival. No parasitised S. viridis were found in the controls.

Reed and Carne (1967) state that laboratory experiments to assess nematode parasitism can be misleading due to the absence of preferred hosts which may exist in field situations. It is also possible that nematodes may have difficulty in parasitising a mobile collembolan such as S. viridis in the field. However, climatic conditions which favour S. viridis, i.e. greater than 70% relative humidity and mean temperatures around 13^{o}C (MacLagan 1932a), are also the conditions under which Miller and Bedding (1982) achieved high levels of parasitism of the currant borer, Synanthedon tipuliformis, when S. bibionis was sprayed onto blackcurrants.

The high levels of parasitism observed in this laboratory study suggest that future evaluation of field applications of entomogenous nematodes for control of S. viridis is warranted.

CHAPTER 8

IDENTIFICATION, DISTRIBUTION AND PHENOLOGY OF THE SURFACE-ACTIVE COLLEMBOLA OF TASMANIAN PASTURES

INTRODUCTION

Womersley (1932, 1939) recorded about 16 collembolan species from the Tasmanian culture steppe and these included a number of species collected from pastures. However, it is uncertain how many were actually collected from this habitat because he did not publish specific details on collection sites. Apart from this taxonomic contribution by Womersley, the only other work published on Tasmanian pasture Collembola prior to the commencement of the investigations reported here, involved studies on S. viridis because of its pest status. Davidson (1934) included Tasmania in a series of maps showing the possible limits of S. viridis in Australia, Evans (1937) studied the seasonal abundance of S. viridis at West Devonport and Wallace and Mahon (1971) included Tasmanian collected data in further work on the distribution of S. viridis in Australia.

This Chapter presents the results of surveys and population monitoring carried out in Tasmania during the period 1976-84 which has enabled (i) the identification of the surface active fauna, (ii) the determination of the distribution and phenology of individual species and (iii) an examination of how weather parameters (temperature, rainfall and the rainfall : evaporation ratio) may affect populations of individual species.

MATERIALS AND METHODS

(i) Collection techniques

(a) Surveys

From May 1977 to July 1984 the collembolan fauna collected in each of 239 pastures sampled in different localities throughout Tasmania was examined. Samples were collected using a portable back-pack suction machine. The use of this machine and subsequent examination of collected samples is detailed in Chapter 2. Distribution of species were examined in relation to the climatic zones of Walter and Lieth (1967) and the division of pastures into wet and dry ecotypes (McQuillan and Ireson 1982) as discussed in Chapter 3. Possible preferences for season or ecotype were examined using the log-linear model technique of McCullagh and Nelder (1983) as done for S. viridis and acarine predators (Chapters 3 and 5). The collection data were also used as an indicator of the relative frequency of occurence of species in pasture.

(b) Sample plots

Monthly monitoring of sample plots was carried-out at high rainfall (wet) sites using the core sampling method. A description of evaluation of this technique together with the method of examination is described in Chapter 2. The sites were originally selected at Moriarty, Elliott and Flowerdale (see Chapter 3, Fig. 3.5) to monitor populations of S. viridis from May 1976 but counts of other Collembola were included from September 1976. A full description of the sample sites and sample periods at Moriarty (Moriarty 1 and Moriarty 2), Elliott and Flowerdale is given in Chapter 4. A third site at Moriarty (Moriarty 3) was sampled monthly

over a 12 month period from November 1981 to October 1982 to monitor a population of the neanurid, Brachystomella platensis Najt and Massoud which was not present at the other sites. The Moriarty 3 site was an 0.1 ha unfenced plot selected near the centre of a relatively flat 3 ha pasture grazed periodically by cattle. The floral composition was chiefly ryegrass and white clover with patches of cocksfoot and subterraneum clover. Broad leaf weeds consisted mostly of Plantago sp., Erodium moschatum and Rumex sp. The soil type was Krasnozem.

(ii) Sorting, examination and identification procedures
The methods used to sort and examine species collected in suction and core samples are given in Chapter 2. A key to the identification of species is presented in Chapter 13.

(iii) Effect of weather parameters on population fluctuations
Monthly individual species counts for all sites were compared with mean temperature and rainfall recorded for each site. Mean daily pan evaporation was recorded only at Elliott and this was used to calculate the rainfall : evaporation (R/E) ratio and enabled comparison of this parameter with the monthly collembolan counts (Elliott only). The use of the R/E ratio was discussed in Chapter 3.

Comparisons of monthly population fluctuations with temperature, rainfall and the R/E ratio were made with the weather parameters being calculated over the following periods:

(i) the 14 day period prior to each sample date
(ii) the 14 day period 14-28 days prior to each sample date (14 day lag' period)
(iii) the 28 day period prior to each sample date
(iv) the 28 day period 14-42 days (14 day 'lag') prior to each sample date
(v) the 28 day period 28-56 days (28 day 'lag') prior to each sample date

The data were then analysed to determine the correlation between collembolan numbers and the abovementioned parameters over the periods indicated. Because there was often a wide range in species numbers between sample dates, log transformations were carried out on the data to normalise the spread.

Mean monthly temperature and total rainfall figures for Elliott Research Station and the stations nearest to Moriarty (East Devonport) and Flowerdale (Wynyard West) are presented in Figs 8.1, 8.2 and 8.3.

RESULTS

(i) Identification and occurrence
Table 8.1 lists 42 surface-active species from 6 families identified during surveys (euedaphic species collected are appended at the end of

Table 8.1 Surface-active species of Tasmanian pasture Collembola and their frequency of occurrence in 239 samples.

Species*	No. of collections in wet pastures (n=150)	No. of collections in dry pastures (n=89)	Collections (wet + dry) as % of total samples
Dicyrtomidae			
cf. Dicyrtomina sp. 1	8	0	3.4
Sminthuridae			
Sphaeridia pumilis (Krausbauer grp.)	78	37	48.1
Jeannerotia stachi australiensis Betsch and Massoud	9	3	5.0
Sminthurides sp.1	5	1	2.5
Katianna australia Womersley	76	16	38.5
Katianna mucina Womersley	10	2	4.2
Katianna sp. cf. obscura (Womersley)	1	0	0.4
Katianna oceanica var. schoetti Womersley	87	27	47.7
Katianna ornata Womersley	13	0	5.0
Katianna sp. cf. pescotti Womersley	1	3	1.7
Katianna sp. 1	43	3	19.2
Sminthurinus elegans (Fitch)	55	30	35.6
Sminthurinus mime Boerner	1	0	0.4
Sminthurinus tuberculatus Delamare and Massoud	3	1	1.7
Sminthurinus sp. 1	1	3	1.7
Deuterosminthurus sulphureus meditteraneus Ellis	5	3	3.4
Prorastriopes quinquefasciatus (Krausbauer)	2	5	2.9
Bourletiella hortensis (Fitch)	1	0	0.4
Bourletiella viridescens Stach	89	34	51.5
Corynephoria sp. 1	0	1	0.4
Sminthurus viridis (L.)	46	10	23.4
Entomobryidae			
Australotomurus echidnus Womersley	1	0	0.4
Entomobrya sp. cf. lanuginosa (Nicolet)	27	22	20.5
Entomobrya marginata (Tullberg)	86	53	58.2
Entomobrya multifasciata (Tullberg)	63	57	50.2
Entomobrya unostrigata Stach	0	7	2.9
Lepidocyrtoides spp.	2	2	1.7
Lepidocyrtus sp. 1	4	0	1.7
Isotomidae			
Isotomurus palustris (Mueller) group	108	49	65.7
Isotoma notabilis Schaeffer	18	4	9.2
Isotoma tigrina (Nicolet)	38	1	16.3
Cryptopygus thermophilus (Axelson)	37	21	24.3
Hypogastruridae			
Hypogastrura (Ceratophysella) denticulata (Bagnall)	17	12	12.1
Hypogastrura sp. cf. engadinensis Gisin	9	18	11.3
Hypogastrura (C.) gibbosa (Bagnall)	0	2	0.8
Hypogastrura (Hypogastrura) assimilis (Krausbauer)	3	2	2.1
Hypograstrura (H.) manubrialis (Tullberg)	2	13	6.3

Table 8.1 Surface-active species of Tasmanian pasture Collembola and their frequency of occurrence in 239 samples. (cont.)

Species*	No. of collections in wet pastures (n=150)	No. of collections in dry pastures (n=89)	Collections (wet + dry) as % of total samples
Hypogastrura (H.) purpurescens (Lubbock)	0	1	0.4
Hypogastrura (H.) vernalis (Carl)	6	22	11.7
Triacanthella sp. 1	2	1	1.3
Neanuridae			
Brachystomella platensis Najt and Massoud	33	54	36.4
Neanura muscorum (Templeton)	1	0	0.4

* Euedaphic species were sometimes identified in suction samples taken from pastures during surveys or collected from core samples. Species identified were as follows:

Onychiurus sp. armatus (Tullberg) group)
Onychiurus sp. fimetarius (L.) group)
Tullbergia sp.)

Occurrence in pasture also discussed in Chapter 10. Onychiurus spp. were ocassionally collected from both core and suction samples. Tullbergia was identified in only one instance in a core sample from the Flowerdale site.

Entomobryidae

Preudosinella sp. nr. alba (Packard) was common in core samples taken at Moriarty (1 and 2), Elliott and Flowerdale. It was not collected in suction samples.

Isotomidae

Small numbers of Isotomides productus (Axelson) were recorded at the Flowerdale site from core samples in two instances.

Isotomiella minor Schaeffer was recorded in one instance in a soil sample (taken in pasture at Hamilton).

the Table) and their relative frequency of occurrence in samples. The total collections for each species expressed as a percentage of the number of samples taken is considered to be a reasonably accurate index to the relative frequency of occurrence of each species in pastures, when considered in conjunction with data obtained on seasonality and pasture ecotype preference. Most of the collembolan fauna of improved pastures is composed of introduced (cosmopolitan) species and none are known to be endemic to Tasmania (see Table 13.3). Examination of Table 8.1 shows that the most common of all (and probably the most common species in the Tasmanian culture steppe) is I. palustris. Of the other introduced species, the entomobryids E. marginata and E. multifasciata and the sminthurid B. viridescens were also common, being identified in over 50% of collected samples. The sminthurids S. viridis (see Chapter 3), S. pumilis and S. elegans, the entomobryid E. lanuginosa, the isotomid C. thermophilus and the neanurid B. platensis were all relatively common and were collected in 20-50% of samples. Less common were the isotomids I. tigrina (16.3%) and I. notabilis (9.2%). The Hypogastruridae are discussed in detail in Chapter 8, however, H. sp. cf. engadinensis, H. vernalis and H. denticulata all occurred at a similar level of frequency (ca 12%). All remaining introduced species were identified in ca 6% or less of samples. Among these were the sminthurids, Sminthurides sp. a hydrophilic species (King et al 1976), the Sminthurinus species S. mime, S. tuberculatus and Sminthurinus sp. 1. and the hypogastrurid, Triacanthella sp. which was only located in central and sub-alpine areas. Of the native species, K. australia, K. oceanica var. schoetti and to a lesser extent K. sp. 1 were the most successful of the 7 Katianna species in exploiting sown pastures from their original native grassland habitat. The Corynephoria species which was collected in only one instance was probably a vagrant from its native grassland habitat (Ireson unpubl. data). Of the native entomobryids, populations of A. echidnus were collected on only one occasion and those of Lepidocyrtoides spp. on 4 occasions from sown pasture. In native habitats, A. echidnus and Lepidocyrtoides have been collected from native grasses and extracted from forest ground litter (Ireson unpubl. data). It seems that these may occasionally appear in sown pasture by entering this habitat from nearby native vegetation or survive for short periods of time following the clearing of native vegetation on land sown for pasture. Lepidocyrtus sp. 1 was collected only from wet pastures on 4 occasions. It is possible that this is a native species of rare occurrence in sown pastures, however, it has not been collected in samples from a range of native habitats (Ireson unpubl. data). Obviously, further sampling is needed to determine its distribution.

(ii) Distribution and phenology

The seasonal distribution of the 239 samples taken during the 9 year study period is given in Table 8.2. Collection sites for surface-active species are indicated in Figs 8.4 - 8.44. Table 8.3 gives the results of analyses of survey data and indicates significance levels for occurrence

Table 8.2 Seasonal distribution of survey collections from wet pastures (mean annual rainfall > 800 mm) and dry pastures (mean annual rainfall < 800 mm) during the period 1976 - 1984 in Tasmania.

	No. of pastures sampled				
	Spring	Summer	Autumn	Winter	Total
Wet pastures	44	34	63	9	150
Dry pastures	16	21	14	38	89
Total	60	55	77	47	239

Table 8.3 Results of survey data analysis for determination of possible ecotype or seasonal preferences of common surface-active species in pastures.

Species	Season	% High rainfall	% Low rainfall	% Total
cf. Dicyrtomina sp. 1	Spring	4.5	0	3.3
	Summer	0	0	0
	Autumn	9.5	0	7.8
	Winter	0	0	0
	X^1_2 (high/low) = 7.61**			
	X^1_3 (seasonal) = 10.48**			
S. pumilis	Spring	65.9	68.8	66.7
	Summer	32.4	28.6	30.9
	Autumn	50.8	21.4	45.4
	Winter	66.7	44.7	48.9
	X^1_2 (high/low) = ns			
	X^1_3 (seasonal) = 15.34**			
J. stachi australiensis	Spring	2.3	6.3	3.3
	Summer	0	0	0
	Autumn	12.7	0	10.4
	Winter	0	5.3	0
	X^1_2 (high/low) = ns			
	X^1_3 (seasonal) = 9.74**			
K. australis	Spring	65.9	18.8	53.3
	Summer	23.5	19.0	21.8
	Autumn	58.7	0	48.1
	Winter	22.2	23.7	23.4
	X^1_2 (high/low) = 26.79**			
	X^1_3 (seasonal) = 20.16**			
K. mucina	Spring	4.5	6.2	5.0
	Summer	5.9	0	3.6
	Autumn	1.6	0	3.6
	Winter	33.3	2.6	8.5
	X^1_2 (high/low) = ns			
	X^1_3 (seasonal) = ns			
K. oceanica var. schoetti	Spring	70.5	43.8	63.3
	Summer	35.3	28.6	32.7
	Autumn	61.9	7.1	51.9
	Winter	55.6	34.2	38.3
	X^1_2 (high/low) = 17.42**			
	X^1_3 (seasonal) = 13.22**			

Table 8.3 (cont.) Results of survey data analysis for determination of possible or seasonal preferences of common surface-active species in pastures.

Species	Season	% High rainfall	% Low rainfall	% Total
K. ornata	Spring	11.4	0	8.3
	Summer	2.9	0	1.8
	Autumn	11.1	0	9.0
	Winter	0	0	0
	X^1_2 (high/low) = 12.55**			
	X^1_3 (seasonal) = 9.65*			
K. sp. 1	Spring	36.4	0	26.7
	Summer	5.9	9.5	7.3
	Autumn	36.5	0	29.9
	Winter	22.2	2.6	6.4
	X^1_2 (high/low) = 28.14**			
	X^1_3 (seasonal) = 19.64*			
S. elegans	Spring	38.6	68.8	46.7
	Summer	20.6	23.8	21.8
	Autumn	46.0	14.3	40.3
	Winter	22.2	31.6	29.8
	X^1_2 (high/low) = n.s			
	X^1_3 (seasonal) = 9.45*			
D. sulphureus mediteranneus	Spring	0	0	0
	Summer	14.7	9.5	12.7
	Autumn	0	0	0
	Winter	o	2.6	2.1
	X^1_2 (high/low) = ns			
	X^1_3 (seasonal) = 18.47**			
P. quinquefasciatus	Spring	0	0	0
	Summer	5.9	23.8	12.7
	Autumn	0	0	0
	Winter	0	0	0
	X^1_2 (high/low) = ns			
	X^1_3 (seasonal) = 21.30**			

Table 8.3 (cont.) Results of survey data analysis for determination of possible ecotype or seasonal preferences of common surface-active species in pastures.

Species	Season	% High rainfall	% Low rainfall	% Total
B. viridescens	Spring	63.6	68.8	65.0
	Summer	73.5	42.9	61.8
	Autumn	55.6	14.3	48.1
	Winter	11.1	31.6	27.7
	χ^1_2 (high/low) = 10.05**			
	χ^1_3 (seasonal) = 18.22)**			
E. lanuginosa	Spring	9.1	12.5	1.0
	Summer	20.6	14.3	18.2
	Autumn	22.2	21.4	22.1
	Winter	22.2	36.8	34.4
	χ^1_2 (high/low) = ns			
	χ^1_3 (seasonal) = 9.74**			
E. marginata	Spring	38.6	37.5	38.3
	Summer	64.7	57.1	61.8
	Autumn	65.1	71.4	66.2
	Winter	66.6	65.8	66.0
	χ^1_2 (high/low) = ns			
	χ^1_3 (seasonal) = 13.15**			
E. multifasciata	Spring	38.6	62.5	45.0
	Summer	52.9	57.1	54.5
	Autumn	41.3	78.6	48.1
	Winter	22.2	36.8	34.0
	χ^1_2 (high/low) = 10.97**			
	χ^1_3 (seasonal) = ns			
E. unostrigata	Spring	0	0	0
	Summer	0	9.5	3.6
	Autumn	0	14.3	2.6
	Winter	0	7.9	6.4
	χ^1_2 (high/low) = 14.19**			
	χ^1_3 (seasonal) = ns			

Table 8.3 (cont.) Results of survey data analysis for determination of possible ecotype or seasonal preferences of common surface-active species in pastures.

Species	Season	% High rainfall	% Low rainfall	% Total
I. palustris	Spring	95.5	75.0	90.0
	Summer	26.5	23.8	25.5
	Autumn	76.2	21.4	66.2
	Winter	100.0	76.3	80.9
	χ^1_2 (high/low) = 7.03**			
	χ^1_3 (seasonal) = 61.59**			
I. notabilis	Spring	36.4	0	26.7
	Summer	22.9	0	1.8
	Autumn	28.6	0	23.4
	Winter	33.3	2.6	8.5
	χ^1_2 (high/low) = 4.16*			
	χ^1_3 (seasonal) = 8.92*			
I. tigrina	Spring	36.4	0	26.7
	Summer	2.9	0	1.8
	Autumn	28.6	0	23.4
	Winter	33.3	2.6	8.5
	χ^1_2 (high/low) = 31.91**			
	χ^1_3 (seasonal) = 21.97**			
C. thermophilus	Spring	22.7	37.5	26.7
	Summer	11.8	19.0	14.5
	Autumn	34.9	7.1	29.9
	Winter	11.1	26.3	23.4
	χ^1_2 (high/low) = ns			
	χ^1_3 (seasonal) = ns			
B. platensis	Spring	27.3	43.8	31.7
	Summer	14.7	23.8	18.2
	Autumn	25.4	92.9	37.7
	Winter	33.3	76.3	61.7
	χ^1_2 (high/low) = 36.05**			
	χ^1_3 (seasonal) = 21.78**			

Significance levels χ^1_2, 5% = 3.84 χ^1_3, 5% = 7.81
χ^1_2, 1% = 6.63 χ^1_3, 1% = 11.3

in wet or dry pastures and any seasonal interactions. Only species that show significant interactions are included in this Table. Obviously some species were collected in only isolated instances and in numbers too small from both surveys and monitored plots to enable the manifestation of any significant trends.

Monthly variations in populations of individual species at monitored sites are indicated in Figs 8.45 - 8.101. A summary of the activity of the common surface-active species recorded at each of the monitored sites is given in Table 8.4. Comparison with Table 8.1 indicates that the species recorded in highest numbers in monitored plots were also among the most frequently collected species in suveys.

Data from surveys is generally supported by results from monitored sites in the high rainfall pastures. Results from the latter show species have regular annual cycles, although there was some variation in patterns of seasonal periodicity. S. viridis was the most numerically dominant species at these sites from autumn through to spring (Figs 8.75 - 8.78). The largest populations of other common species were usually recorded in autumn or spring months (Table 8.4), the main exceptions being the entomobryids E. marginata and E. multifasciata and the sminthurids P. quinquefasciatus and D. sulphureus mediterraneus. These latter two species were collected only in relatively small numbers from survey and core samples, however, examination of both data sets (Tables 8.3, 8.4. Figs 8.67 - 8.69) indicate that summer is their main period of activity. Summer maxima were also shown for both E. multifasciata and E. marginata, the latter species being dominant at wet sites from mid-summer until the breaking rains of autumn (Figs 8.79 - 8.86). This is reflected in the survey data analysis (Table 8.3) which indicate a preference by E. multifasciata for dry pastures. The species was collected from a higher proportion of pastures sampled in summer than in other seasons during surveys of wet pastures, however, no overall seasonal interaction is indicated. This can be attributed to an increase in the percentage frequency of the species in collections from dry pasture during spring, autumn and winter as opposed to summer.

Although monitored populations of E. marginata showed summer maxima, active stages were collected in core samples in all seasons, the lowest period of activity usually being late winter/early spring (Figs 8.79 - 8.82). Unlike E. multifasciata no significant preference for wet or dry sites was shown from analysis of the survey data, the species showing extended periods of seasonal activity at both wet and dry sites. Collections of this species taken in summer, autumn and winter were equally proportioned compared to fewer collections in spring (Table 8.3). The other entomobryids were not collected from core samples so less is known of their phenology, however, the survey results show that populations of E. lanuginosa clearly showed trends similar to E. marginata. E. unostrigata was only collected from dry pastures in small

Table 8.4 Summary of activity of surface-active Collembola recorded in sample plots with poulations exceeding 1000/m^2 on any sample date.

Species	Sites were populations identified	Populations exceeding 1000/m^2 Summer	Autumn	Winter	Spring	Maximum population recorded (nos./m^2)*
Dicyrtomidae						
cf. Dicyrtomina sp. 1	M2, E, F	-	+	+	+	4105 (F) (21.10.79)
Sminthuridae						
S. pumilis	M1, M2, E, F	-	-	-	+	4056 (M1) (17.10.77)
K. australis	M1, M2, E, F	+	+	+	+	5231 (E) (14.4.77)
K. oceanica var.schoetti	M2, E, F	+	+	-	+	2333 (E) (14.04.77)
S. elegans	M2, E, F	+	-	-	+	2321 (F) (21.11.77)
B. viridescens	M1, M2, E, F	+	-	-	+	6631 (E) (27.11.78)
S. viridis	M1, M2, E, F	-	+	+	+	51,587 (F) (26.06.78)
Entomobryidae						
E. marginata	M1, M2, E, F	+	+	-	-	9050 (F) (24.03.80)
Isotomidae						
I. palustris	M1, M2, E, F	-	+	+	+	8355 (M2) (24.09.79)
I. notabilis	M2, E, F	+	+	-	+	5346 (E) (07.12.76)
C. thermophilus	M1, M2, E, F	+	+	+	+	4552 (M1) (24.05.77)
Neanuridae						
B. platensis	M3	+	+	+	+	8847 (M3) (25.05.82)

* Although populations of the entomobryid E. multifasciata (M1, M2, E - maximum population 541/m^2 (M2) on 17.01.77) and the sminthurids, D. sulphureus meditteraneus (F - maximum populations 34/m^2 on 18.12.78, 22.01.79. 21.01.80) and P. quinquefasciatus (M1, M2 - maximum population 89/m^2 (M1) on 17.01.77) were lower than the species listed above, core sampling indicated that population maxima of these species were attained in summer.

numbers but probably has a similar affinity to the dry pasture ecotype as exemplified by E. multifasciata.

Seasonal trends for the isotomid I. palustris (Figs 8.87 - 8.90) and the dicyrtomid, cf. Dicyrtomina sp. 1 (Figs 8.45 - 8.47) were similar to those recorded for S. viridis (Figs 8.75 - 8.78). For these species active stages were absent or at low levels during the drier summer months at all sites, with activity stimulated by the onset of autumn rains. Autumn/early winter populations were followed by a decrease in activity during the coolest winter months and population increases during spring.

The survey data for the isotomids I. notabilis and I. tigrina show a preference by both species for wet pastures and highest activity during spring and autumn (Table 8.3). Similarly, at monitored sites, although I. tigrina occurred only at Moriarty 2 in small numbers (Fig. 8.94) all collections were made during spring and autumn. For I. notabilis activity at monitored sites was variable. In general, however, peaks in activity in most years did occur in either spring or autumn, and although the largest population at Elliott was recorded in early summer, 1976 (December) (Table 8.4), numbers usually fell to their lowest annual levels in late summer (Figs 8.91 - 8.93). One noted exception to this was the continued summer activity at all sites during 1979, and was probably a response to the high summer rainfall particularly in January which was 123% above mean at Moriarty, 117% above mean at Elliott and 116% above mean at Flowerdale. Early summer activity for I. notabilis at all sites during 1976/77 may have been associated with the high December rainfall (56%, 58%, 87% above mean at Moriarty, Elliott and Flowerdale respectively) (Figs 8.1, 8.2, 8.3).

The survey results for C. thermophilus gave no indication of pasture ecotype or seasonal preference by this species. Additional data from monitored sites record populations as exceeding 1000/m^2 in all seasons, although this was not a regular occurrence at any site. The largest recorded population was in autumn at Moriarty 1 (Table 8.4), however, the largest populations during 1979 were recorded in summer at all sites. Examination of Figs 8.95 - 8.98 show that the occurrence of summer maxima was not consistent from year to year and in 1979 was probably a response to the high January rainfall. Similarly, the relatively high populations recorded at all sites in January 1977 may have been associated with the high rainfall recorded in December, 1976. Examination of Table 8.4 and Figs 8.48 - 8.51 show that population maxima of the sminthurid S. pumilis were usually recorded in spring, activity decreasing with the onset of dry summer conditions. A significantly higher proportion of spring collections was also indicated from analysis of the survey data (Table 8.3), however, continued activity of small populations in early summer, 1976-77 and throughout summer in 1978-79 at Elliott, Moriarty and Flowerdale may again have been a response to rainfall.

J. stachi australiensis was collected in only a few instances on surveys, and at monitored sites only occasionally appeared in small numbers at Elliott. The few survey collections were made in autumn, winter and spring, the majority being taken during autumn (wet pastures) (Table 8.3). Examination of Figs 8.52 - 8.54 shows that populations were collected mostly during 1978 at Elliott with small numbers continuously active after the autumn break, the maximum population ($182/m^2$) being recorded in the spring of that year.

The largest populations of S. elegans at monitored sites were recorded in spring (Table 8.4), however, the results show that in most years at sites where it was common (Moriarty and Flowerdale), populations remained quite high in summer with smaller numbers also remaining active through autumn and winter (Figs 8.64 - 8.66). Table 8.3 shows that the largest collections of this species during surveys were made in spring and autumn. Of the other sminthurids, population maxima of B. viridescens were also recorded in spring at monitored sites with activity continuing into summer (Table 8.4, Figs 8.71 - 8.74). In addition, the species was recorded in a significantly higher proportion of survey collections during spring and summer in wet pastures (Table 8.3). Although B. hortensis was rare in pasture, the few collections at the Elliott site made during spring (Fig 8.70), suggest the species has a similar phenology to B. viridescens.

The most common of the 7 Katianna species identified, K. australis, K. oceanica var. schoetti and K. sp. 1) (Table 8.2) all showed a preference for the wet pasture ecotype and these, together with K. ornata, were more frequently collected in autumn and spring months (Table 8.3). At monitored sites, population maxima of the most frequently occurring species (K. australis and K. oceanica var. schoetti) were recorded during autumn. However, populations of these exceeded $1000/m^2$ in all seasons except for K. australis during summer and K. oceanica during winter, but not at all sites (Table 8.4, Figs 8.55 - 8.63).

Although the largest populations of the neanurid, B. platensis were recorded at Moriarty 3 in autumn, the results suggest the species tolerates summer conditions in wet pastures quite well, with populations up to $4,529/m^2$ being recorded in February (Fig 8.101). Analysis of the survey results showed that collections were significantly higher in dry pastures during winter months (Table 8.3).

(iii) Effect of weather parameters

Results of analyses to examine corelations of monthly variations in numbers of the most common species in the sample plots with rainfall and mean temperature are shown in Table 8.5 and with the R/E ratio at Elliott in Table 8.6. Species only occasionally collected in small numbers from cores at some sites (eg. J. stachi australiensis and cf. Dicyrtomina sp. 1 at Moriarty 2 and Elliott, and S. elegans at Elliott

(see Figs 8.45, 8.46, 8.52, 8.53, 8.65) were not included in the analysis for that particular site. Perusal of the results shows that significant correlations are more evident with temperature than rainfall, the levels varying between sites, between different sample periods and the periods over which parameters were measured prior to sampling. At Elliott, correlation of species numbers with the R/E ratio over the range of periods tested (Table 8.5) were generally higher than with rainfall as a single variable (Table 8.6). In general, significant negative correlations with mean temperature and/or positive correlations with rainfall and the R/E ratio were evident for species whose main period of activity was autumn through to spring (cf. Dicyrtomina sp. 1, K. australia, K. ornata, S. viridis and I. palustris). Species with spring or summer maxima (B. viridescens, P. quinquefasciatus, E. multifasciata and E. marginata) showed significant positive correlations with temperature and/or significant negative correlations with rainfall and the R/E ratio.

Although B. viridescens showed negative correlations with rainfall at Elliott and Flowerdale (maximum rainfall is usually recorded in winter at these sites), the analysis revealed a significant positive relationship during the January 1979 - December 1979 sample period at Flowerdale (Table 8.5). In this case the relationship can be considered spurious and associated with the high rainfall recorded for this site for January 1979 (116% above mean) and during the spring (78% above mean), when populations were usually at or near maximum levels.

At Flowerdale, the largest populations of K. oceanica were recorded in spring and summer (Fig. 8.61) and significant positive correlations with temperature are indicated (Table 8.5). At Elliott, population maxima were recorded in autumn although no significant correlations with the weather parameters were revealed. No significant correlation between temperature and rainfall was shown for B. platensis at Moriarty 3.

Seasonal population fluctuations of S. pumilis, S. elegans, I. notabilis, and C. thermophilus at monitored sites (Figs 8.48 - 8.51, 8.64 - 8.66, 8.91 - 8.93 and 8.95 - 8.97) were often less predictable than for other species and this was reflected in their response to weather parameters. It seems that for some species population maxima may occur at any time of the year, if the combination of temperature and humidity is suitable. Significant negative correlations with temperature were obtained for S. pumilis at all sites except Flowerdale. A significant positive correlation with temperature was obtained at this site from analysis of data for the two year period from January 1978 to December 1979 (Table 8.5). A possible contributing factor to this result was the relatively high populations recorded during January 1979 at Flowerdale (Fig. 8.51) which may have been associated with the above average rainfall recorded during this month (as discussed in the previous section). Although there were no significant correlations with rainfall at this site (Table 8.5),

significant positive correlations were obtained at the drier Moriarty 2 site (Table 8.5) and with the R/E ratio during the 12 month sample period (January - December 1977) at Elliott (Table 8.9).

The largest populations of S. elegans at Moriarty 2 and Flowerdale were recorded in spring and summer (Figs 8.64, 8.66) and a significant positive correlation with temperature is indicated at Flowerdale (Table 8.5). At Moriarty 2, Table 8.5 shows a significant positive correlation for the 12 month period including October 1978 to September 1979 and a significant negative correlation for the subsequent 12 months (October 1979 - September 1980). A significant positive correlation with rainfall was also shown by this species at this site during this latter sample period (Table 8.5), and the negative relationship with temperature may have been influenced by the summer rainfall (December 1979 - February 1980) for this period which was 28% below average, the drier summer conditions (Fig 8.1) contributing to the low summer activity for the period.

I. notabilis showed some significant positive correlations with rainfall at Moriarty 2, Flowerdale and Elliott (Table 8.5) but no significant correlations with the R/E ratio at the latter site (Table 8.6). There were few significant correlations at any site with mean temperature. At Moriarty 2 and Elliott there were instances of a significant negative correlation with temperature. However, at Flowerdale significant positive relationships with temperature were evident during the 24 month period from January 1978 to December 1979, and this relationship was also evident during the 12 months from January 1979 to December 1979.

At Elliott and Flowerdale, C. thermophilus showed significant positive correlations with temperature, and over the 12 month sample period from January to December 1979, a few significant negative correlations with rainfall at both sites (Table 8.5) and with the R/E ratio at Elliott (Table 8.6). At Moriarty 2, significant positive correlations are indicated for 3 of the 4 sample periods tested, however, a significant negative correlation with temperature shown for the period October 1979 to September 1980 compares to the results obtained at this site for S. elegans over the same period. It is therefore also likely that low summer rainfall may have been a factor that restricted summer populations. Significant negative correlations with temperature were also obtained at Moriarty 1 over the two year period from September 1976 to August 1978 (Table 8.5). At this site, examination of Fig. 8.95 shows that populations consistently exceeded $1000/m^2$ in autumn and spring months and although they also exceeded this level during mid-summer (January 1977), populations recorded over the following summer period (December 1978 to February 1979) did not exceed $30/m^2$. The rainfall recorded for this latter summer period was 40% below average so that low moisture levels may have been a key factor in affecting population size. However, no correlations between numbers of this species and rainfall

were detected at the Moriarty sites.

DISCUSSION

The surface-active collembolan fauna of Tasmanian pastures consists mostly of introduced pre-adapted species, the main exception being the Katianna species that have readily adapted to sown pastures from their native grassland habitat. Most of the fauna are r- strategists (Greenslade and Greenslade 1987) and are generally adapted to culture steppe conditions which are constantly changing as a result of mans activities (Matthews 1976). Apart from the herbivorous S. viridis which is a pest, most of the fauna function as beneficial detritovores at the soil/litter interface, feeding on dead leaves and plant stems, decaying carcasses of invertebrates or on fungi and bacteria usually associated with the breakdown of this material (Greenslade and Greenslade 1983; Brand 1989). A number of species that are active during late spring and summer such as (B. viridescens and D. sulphureus mediterraneus) may also feed on pollen and may even be involved in the pollination process (Kevan and Kevan 1970).

Most of the surface-active Collembola that occur in Tasmanian sown pastures were present in both ecotypes, however, ecotype differences are reflected by the differences in the adaptability of some species, as revealed by the variations in their frequency of occurrences and phenology between each pasture type. Weather parameters are shown to have a significant impact on populations of collembolan species, however, the results often showed that these affects may vary considerably within and between sites over different time periods both intra-and inter-specifically, their impact being governed by a number of other variables.

Correlations between rainfall and collembolan densities were generally less significant than those for temperature, but perhaps this was partly associated with direct rainfall figures not being a measure of effective rain. The R/E ratio is obviously a better indicator of soil moisture conditions at the soil surface (Davidson 1934), and is perhaps the reason why comparatively higher correlations with species numbers were attained at Elliott when rainfall was used in terms of this ratio than as a single variable.

The coefficients of determination for populations of individual collembolan species accounted for by the effects of temperature and rainfall were often high, however, a number of other factors affect population densities either directly or indirectly apart from weather. These include natural enemies (see chapters 3 and 5), competition and the effects of management practices such as grazing, cutting, irrigation and fertiliser applications, all of which can have considerable impacts on collembolan populations over short periods of time (Curry 1987). The extent to which population fluctuations are influenced by any particular factor over a given time period may also be interrelated with a

complexity of other factors, both biotic and physical, and the influence of these may vary according to the favourability of the environment for a particular species (Joosse 1981). For instance, weather conditions during a particular season may have more influence on species numbers in pastures depending on the density and type of grazing animals used during this period. Increasing sheep and cattle numbers cause a corresponding reduction in the number of surface-active Collembola due to the considerable changes in sward microclimate, living space and food (King and Hutchinson 1976); Pottinger et al. 1985) and the impact of these factors could be expected to vary according to prevailing weather conditions. In populations of S. viridis a self-regulatory factor occurs apart from the influence of weather, food and predators. Young nymphs feed on dead bodies of older nymphs and adults, which have accumulated toxic nitrogenous wastes. The impact of this gains importance as populations increase and may bring about a collapse, even when all other environmental conditions are favourable (Wallace 1967). However, it is not known if similar density dependent self-regulatory processes occur in populations of other species. Variations in seasonality are reflected by the different mechanisms species have adopted for survival. Pastures in southern mainland Australia where S. viridis predominantes mainly experience a Mediterranean climate with a lengthy summer dry season of high temperatures and little or no effective rainfall followed by a definite autumn break, the wet season extending from late autumn (May) until early spring (September).

S. viridis is well adapted to survive the dry summers of this climate and lays two types of eggs. Diapausing drought resistant eggs are laid in spring which must be exposed to hot, dry summer conditions before they can hatch with the onset of autumn rains. Subsequent egg batches laid from autumn are of the non-diapausing type that develop and hatch normally until the following spring, when the increasing maturity of food plants triggers the production of diapause eggs (Wallace 1968). In temperate Tasmanian pastures the climate is not Mediterranean. Although maximum rainfall occurs during winter in high rainfall pastures (where S. viridis is common) the rains usually begin earlier in autumn (late March or early April) with cool, wet conditions extending until late spring (November) and often into early summer (December). Additionally, the summers are cooler and wetter than in a typical Mediterranean climate. In Tasmania, therefore, species of surface-active pasture Collembola whose main periods of activity extended from autumn through to spring, may have their periods of activity prolonged, particularly in the wet pasture ecotype, in comparison to mainland pastures subjected to a more Mediterranean-type of climate. The effect of lower temperature and higher rainfall also extends the period of activity for some collembolan species in New Zealand pastures (Dentener 1985).

Conditions at the wetter Flowerdale site and at Elliott and Moriarty 2 during the wet summer of 1978/79 were suitable to enable activity of C.

thermophilus and S. elegans to continue throughout summer. Because of their spring/summer activity, populations were often significantly correlated with temperature increases. However, the significant negative correlations with temperature recorded at Moriarty 2 during the 12 month period from October 1979 - September 1980, for both C. thermophilus and S. elegans, were associated with a dry summer of below average rainfall for that period and demonstrates that the response of species to a particular parameter (in this case temperature) may vary according to the influence and limitations imposed on it by another variable (in this case rainfall).

Species vary considerably in their response to dry conditions (Davies 1929; Joosse 1981). If conditions at a particular site are suitable to enable the survival of active stages, activity will continue until tolerance levels are reached. At this point the stimulae imposed initiate a physiological response triggering off the mechanisms a particular species uses to survive periods of stress (Joosse 1983).

The observations reported here suggest S. viridis does lay eggs that undergo an aestivating diapause in Tasmania. Populations of active stages fell to their lowest in summer, particularly during the drier months of January and February. During these periods active stages, although often absent, were sometimes recorded at low levels of $<10/m^2$ at Moriarty and Elliott and up to $180/m^2$ at Flowerdale. These populations were probably associated with patches of damp poorly drained pasture with green herbage that was often observed at this time, the higher humidity enabling an increase in survival rate. As discussed by Wallace (1968), immature herbage provides no stimulus for the production of diapause eggs so that adults that feed on it will continue to produce eggs that continue to hatch, the active stages surviving if moisture stresses are low and summer temperatures not too high. For this reason, S. viridis is frequently a problem in irrigated pastures in Tasmania, however, extended periods of activity of small populations in non-irrigated pastures during summer make its control more difficult during autumn, due to asynchronous hatching after the onset of autumn rains (as discussed in Chapter 4).

In South Australia Katianna are usually active in winter in areas of high rainfall and a Mediterranean climate, and presumably aestivate in the egg stage (Greenslade 1981). The further north one progresses toward more arid areas, the period during which winter species dominate decreases until they disappear (Greenslade 1974a). Conversely, in the cooler temperate pastures of Tasmania, as demonstrated in this study, the period of activity for Katianna species increases. At the monitored Tasmanian sites, although activity of the two most common Katianna species, K. australis and K. oceanica var. schoetti, was often at the lowest level during summer, the continued presence of active stages throughout summer in some years, particularly of K. oceanica at Flowerdale (with populations up to $1000/m^2$ being recorded), indicates that eggs of these

species may continue to develop normally at these sites even in summer, if conditions are not too dry.

cf. Dicyrtomina sp. and I. palustris, which have similar phenologies to S. viridis, also probably undergo some form of aestivation in the egg stage. Although there is no firm evidence that their eggs undergo diapause, it is known that Dicyrtomina spp. have two kinds of eggs, summer and overwintering, with the latter requiring a longer incubation period (Hale 1965b). Further, the complete absence of the active stages of both these species from mid - to late summer, even during wet periods, suggests that some form of egg diapause may take place, the eggs needing exposure to warm, dry conditions before they hatch after the onset of autumn rains.

Poinsot-Balaguer (1976) found that S. pumilis aestivates in the egg stage in Mediterranean areas and that the eggs undergo diapause, concluding that hatching was regulated by a combination of temperature and humidity changes. In northern Europe, Blancquaert et al. (1982) found that the species lays non-diapause eggs in winter and diapause eggs in summer and in this respect behaved similarly to S. viridis (Wallace 1968). In summer they found that a warm, dry period seemed to cause death of the active stages. However, although the population recovered quite quickly after rainfall, their laboratory observations made it unclear from which eggs the recovery of the population was generated. They discussed the possibility that a factor which was not related to temperature, humidity, photoperiod, food or population density was involved in regulating hatching. In Tasmania, active stages are absent during warm, dry periods in summer, although activity continues through summer if conditions are moist enough as was evident during the wet summer of 1978-79. One would also expect that the species lays both diapause and non-diapausing eggs depending on the conditions and that the mechanism that operates in stimulating egg hatching is similar to that operating in northern Europe, as discussed by Blancquaert et al. (1982).

Apart from the dessication-resistant egg stage there is little information in the literature to suggest what mechanisms other pasture species identified in this study may employ to survive during adverse conditions. Drought may stimulate locomotory activity in some species which may form agregations under conditions of optimal humidity leading to increasing survival rates (Joosse and Groen 1970). Anhydrobiosis has been recorded for Brachystomella (Poinsot 1974) and ecomorphosis, resulting in morphological changes in the cuticle and internal changes that may enable survival of warm, dry conditions, has been described for species of Hypogastruridae and Isotomidae (Joosse 1983).

Testerink (1981) demonstrated that feeding activity may cease during dry periods in summer and during low temperatures in winter, resulting in a low transpiration rate in summer and a lowering of the supercooling point

in winter. As starvation enhances longevity (Joosse and Testerink 1977), species remain inactive until the return of favourable conditions, when all individuals become activated and start to feed simultaneously. This phenomenum may occur with some Hypogastrura species, large numbers of which often appear after heavy rains following a dry spell (Ireson unpubl. data).

Although numbers of most surface-active species in Tasmanian pastures fall to their lowest numbers during dry summers, species that consistently showed significant positive correlations with temperature (the sminthurids B. viridescens, P. quinquefasciatus, S. mediterraneaus and the entomobryids E. multifasciata and E. marginata) obviously have mechanisms that enable their active stages to survive under conditions of low humidity. Collembola devoid of a tracheal system are very susceptible to dry conditions and most species respire through the cuticle (Davies 1929; Joosse and Groen 1970, Joosse 1983). However, species of Bourletiella, Prorastriopes and Deuterosminthurus are similar to S. viridis in having well developed tracheal systems. This results in independence of gaseous exchange across the cuticle which is accompanied by the retention of a cuticular wax layer which reduces evaporation and makes the species less susceptible to water stress (Dallai 1974). Although many Entomobrya species are tolerant of low humidities the actual physiological mechanisms that enable them to do this are, as yet, unknown as the species lack tracheae (Davies 1929, South 1961). However, many Entomobrya have an abundance of setae covering the body and perhaps these may aid in restricting moisture losses.

Although work on the biology of S. viridis by Maclagan (1932a, 1932b) and Wallace (1967, 1968) enables interpretation of field data for this species, little has been done on the biology of the other species of surface-active Collembola identified here. This work should therefore provide a useful basis for future investigations.

Fig. 8.1 Mean monthly temperature and rainfall recorded at Moriarty (Devonport East) (April 1976 - November 1980; October 1981 - October 1982).

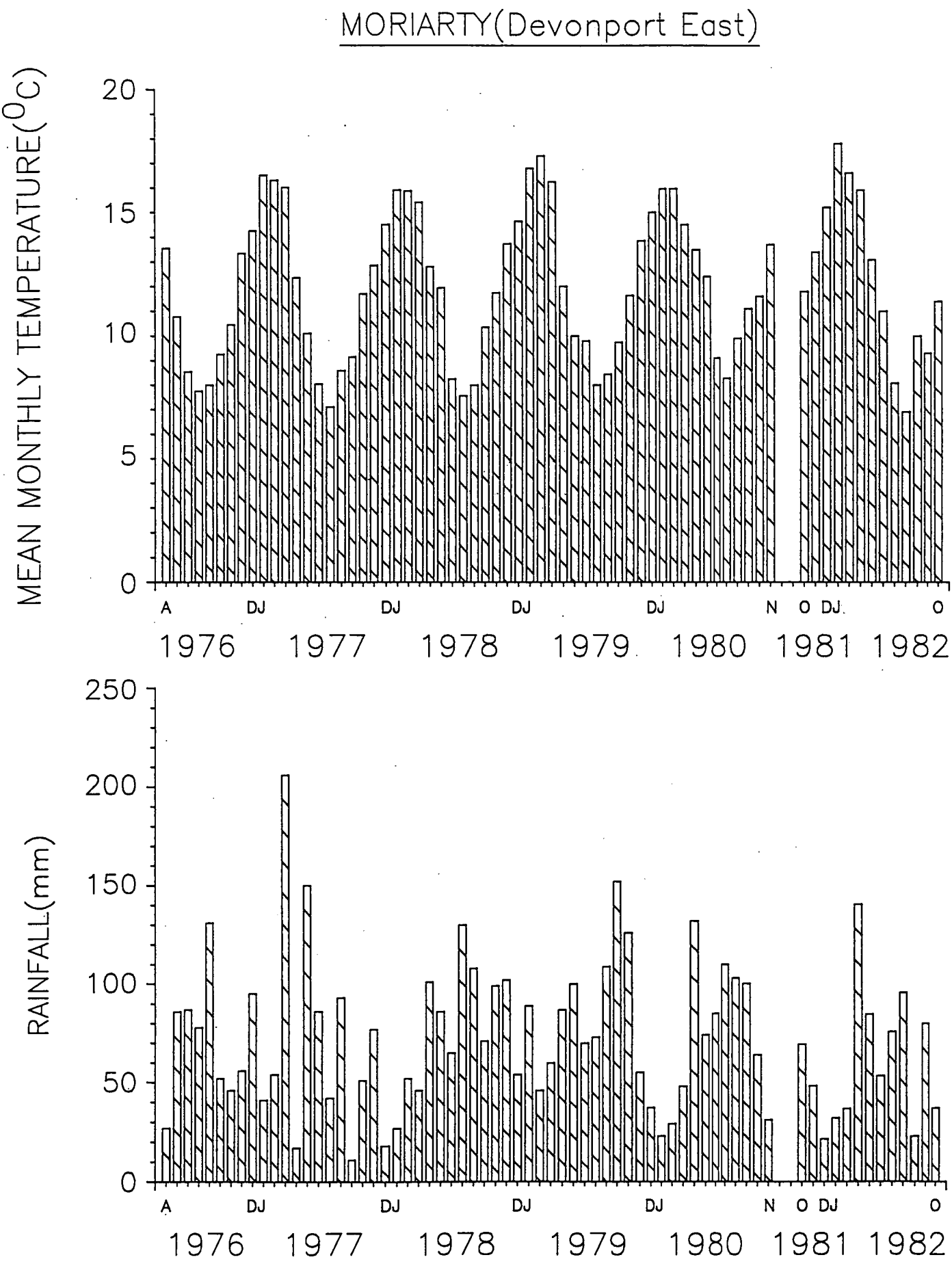
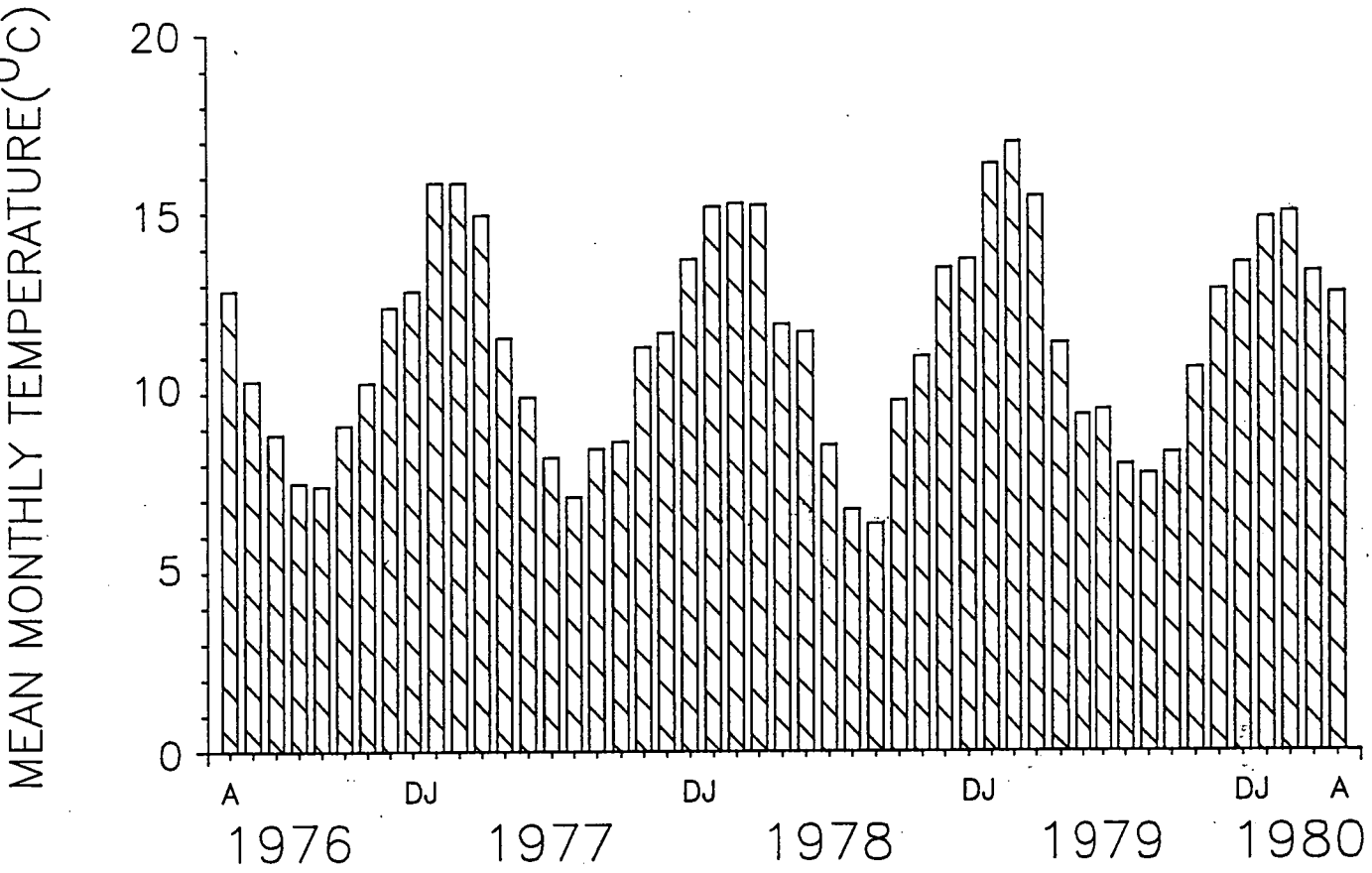

MORIARTY(Devonport East)
MEAN MONTHLY TEMPERATURE(°C)
20
15
10
5
0
A
DJ
DJ
DJ
DJ
N
O
DJ
O
1976
1977
1978
1979
1980
1981
1982
RAINFALL(mm)
250
200
150
100
50
0
A
DJ
DJ
DJ
DJ
N
O
DJ
O
1976
1977
1978
1979
1980
1981
1982

Fig. 8.2 Mean monthly temperature and rainfall recorded at Elliott Research Station (Elliott) (April 1976 - April 1980).

ELLIOTT


MEAN MONTHLY TEMPERATURE(°C)
20
15
10
5
0
A
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

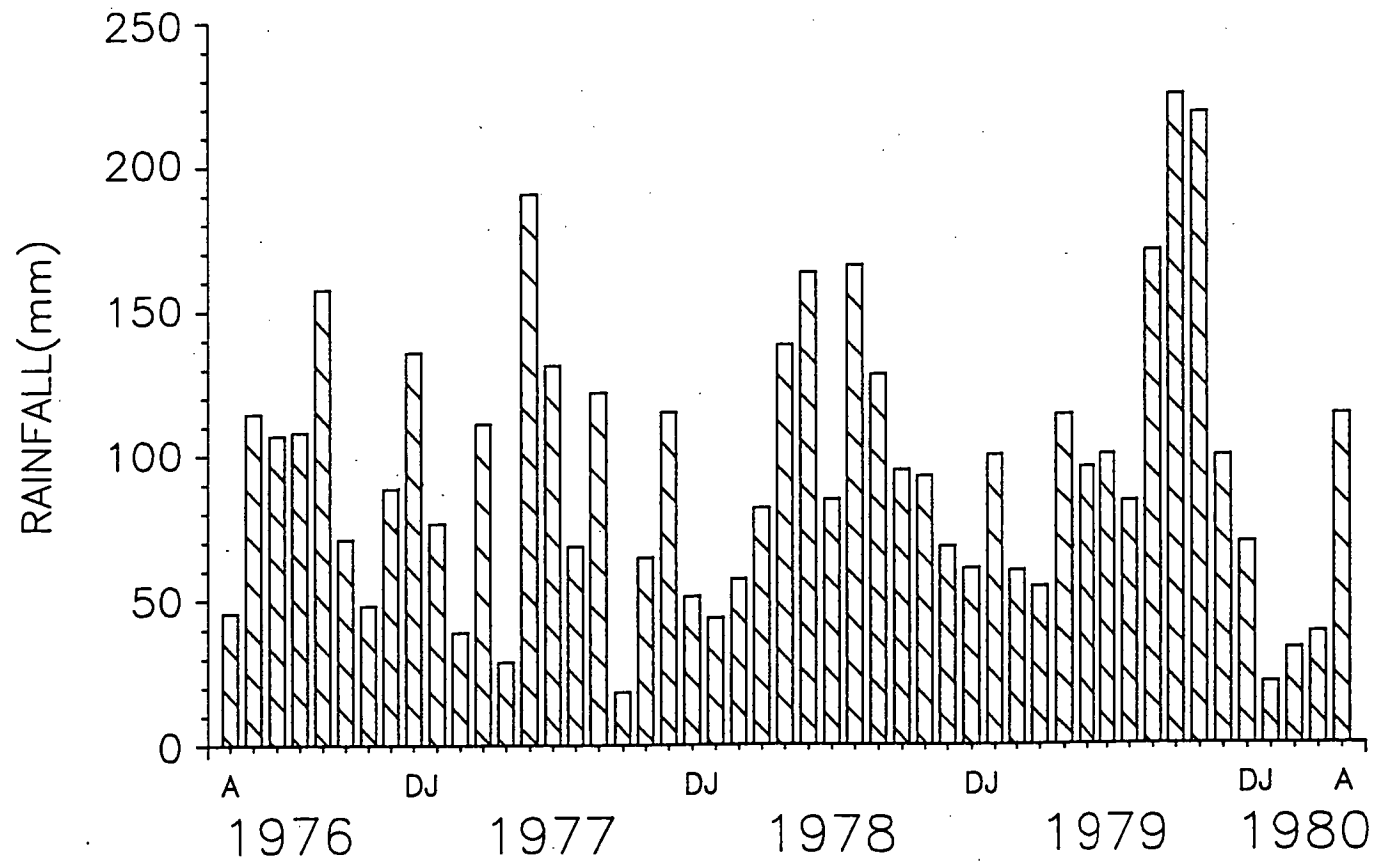
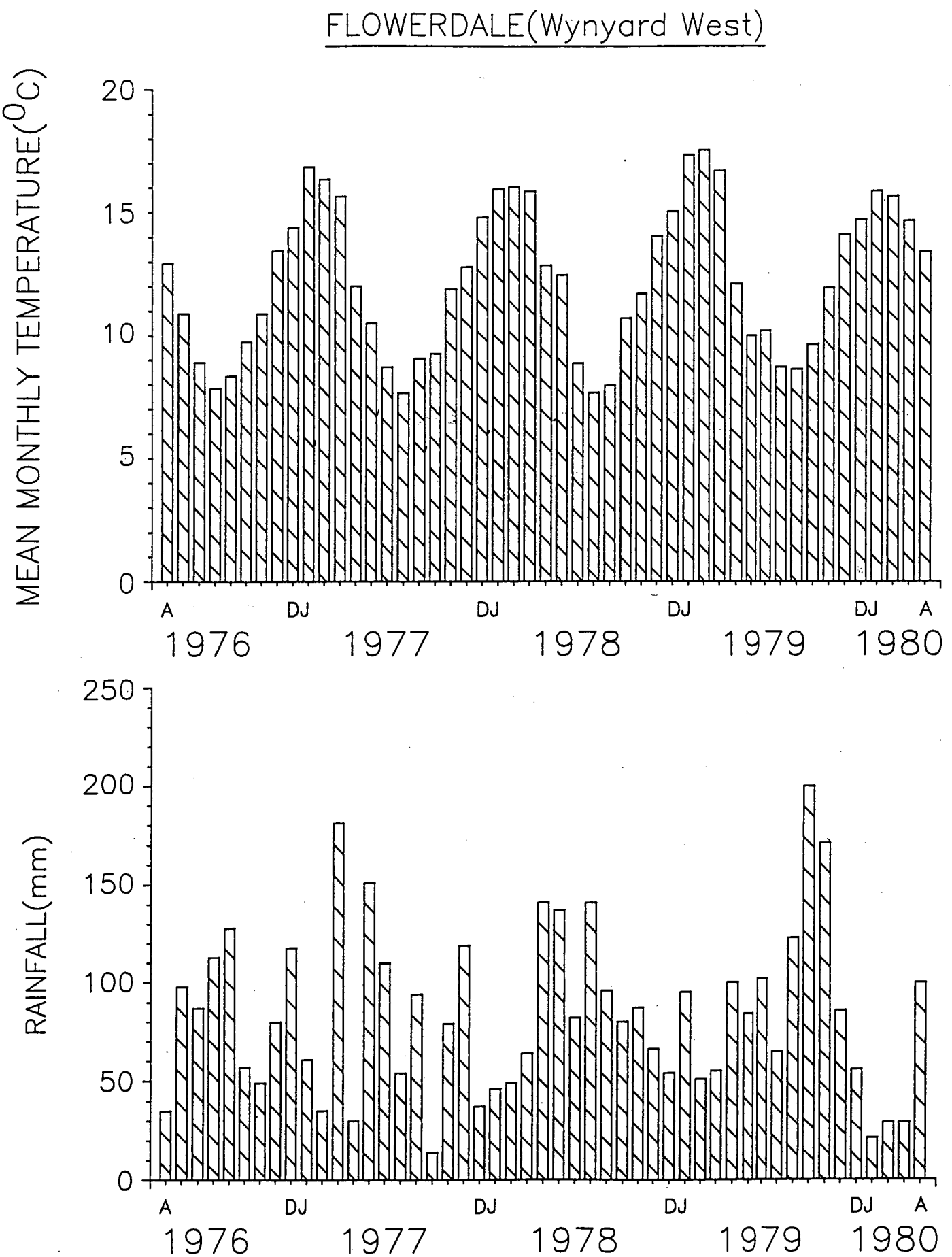
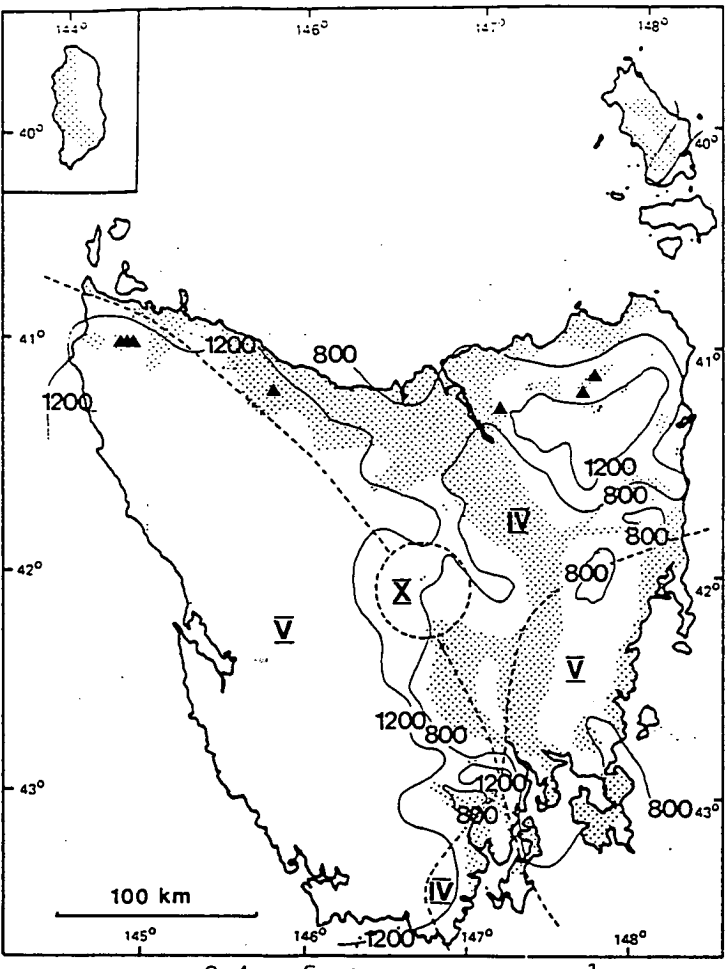

RAINFALL(mm)
250
200
150
100
50
0
A
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

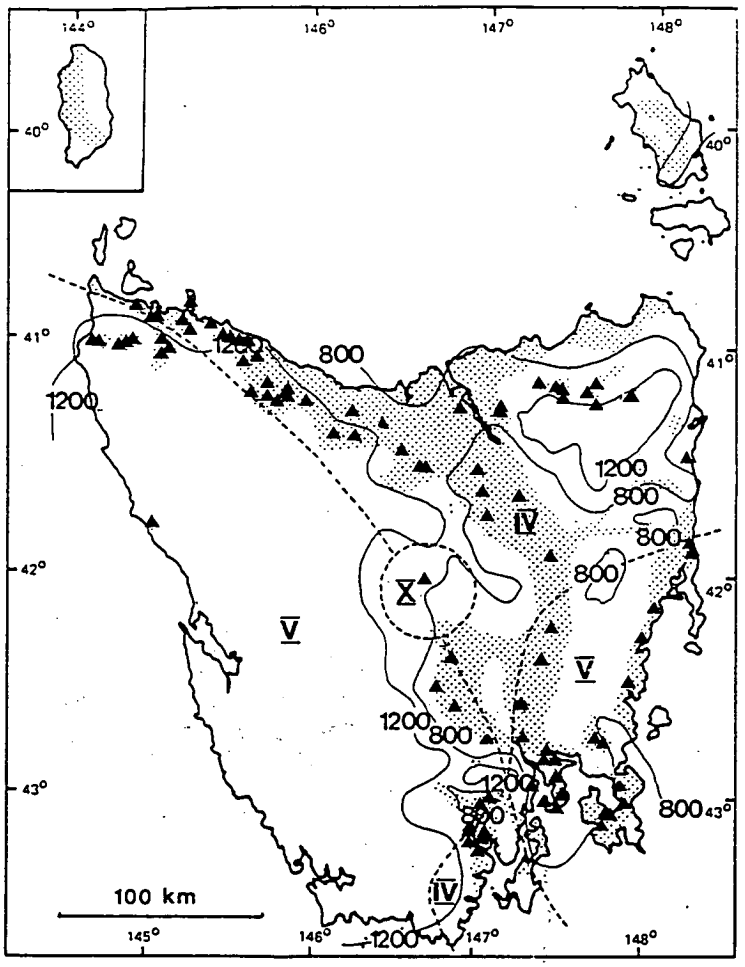
Fig. 8.3 Mean monthly temperature and rainfall recorded at Flowerdale (Wynyard West) (April 1976 - April 1980).


FLOWERDALE(Wynyard West)
MEAN MONTHLY TEMPERATURE(°C)
20
15
10
5
0
A
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980
RAINFALL(mm)
250
200
150
100
50
0
A
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

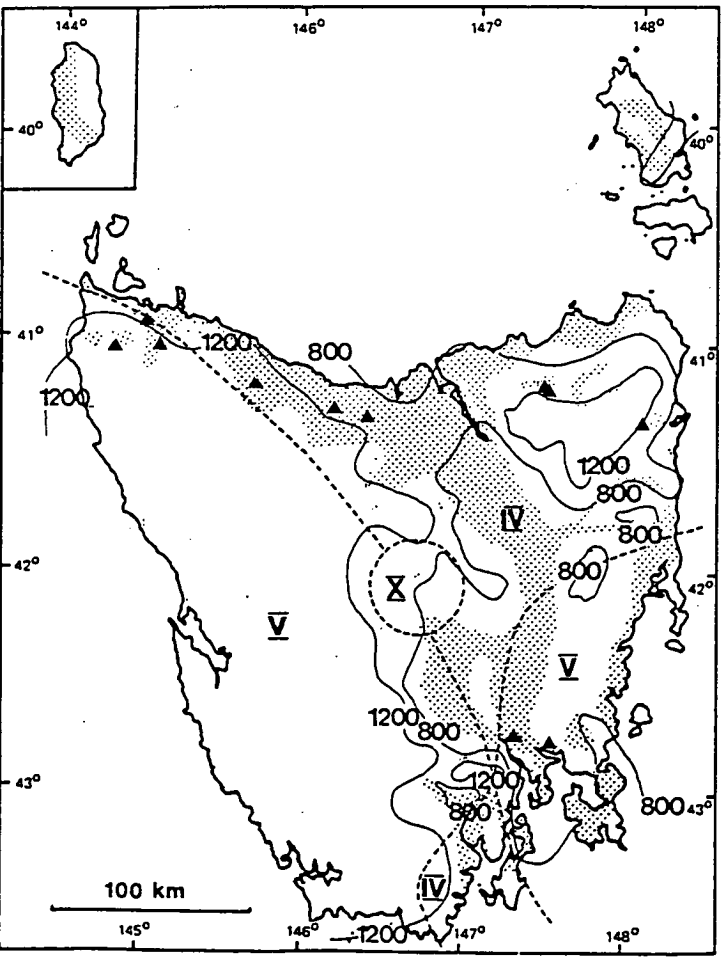
Figs 8.4 - 8.44 Collection sites for individual surface-active collembolan species in Tasmanian pastures in relation to the climatic zones of Walter and Lieth (1967) and the 800 and 1200 mm annual isohyets (stippling on each map is equivalent to the approximate area of sown pasture, ca 900,000 ha).



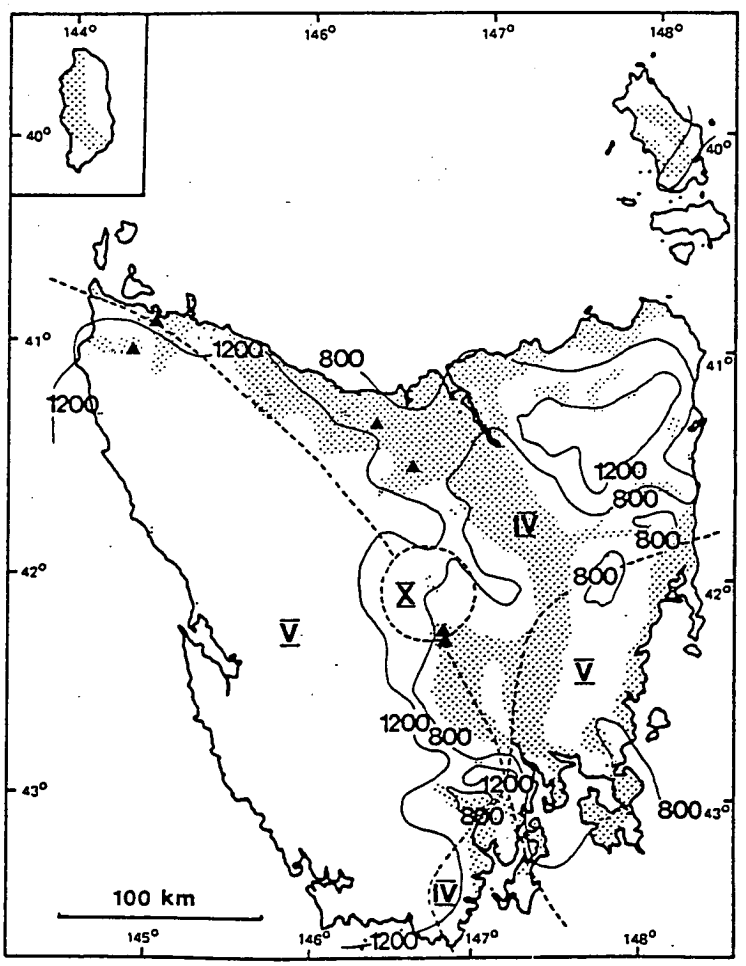
8.4. cf *Dicyrtomina* sp. 1



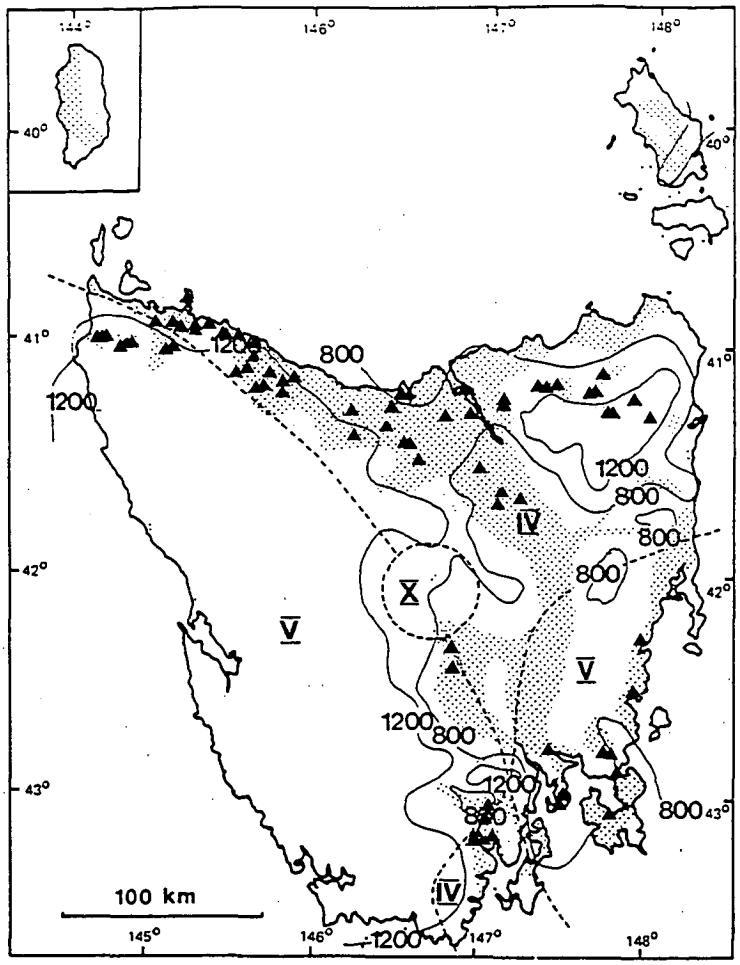
8.5. *S. pumilis*



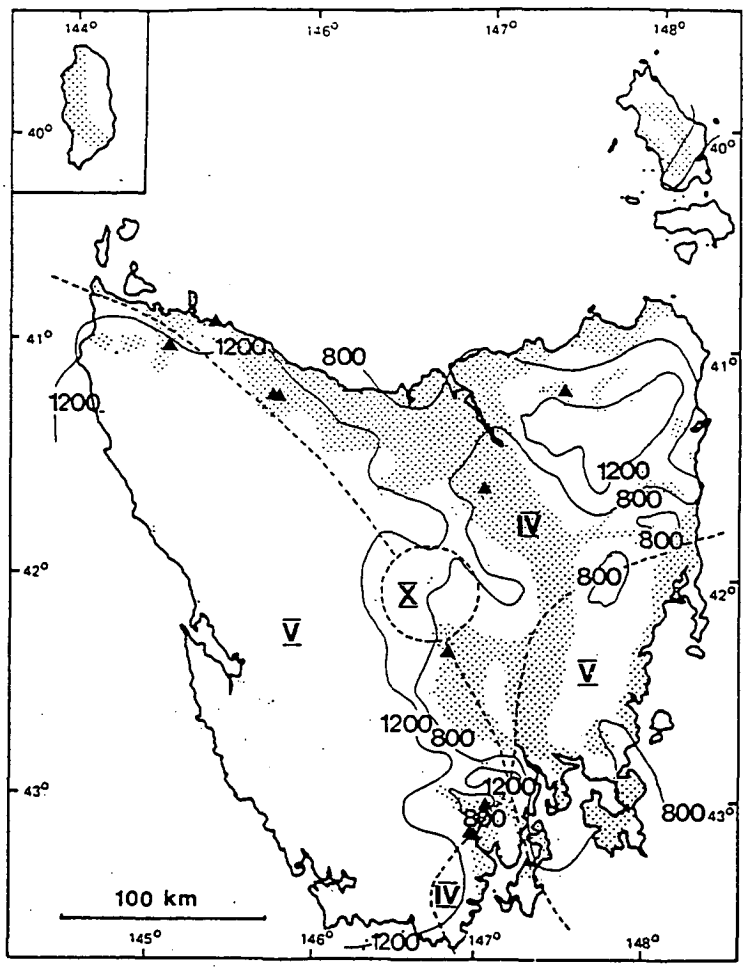
8.6. *J. stachi australiensis*



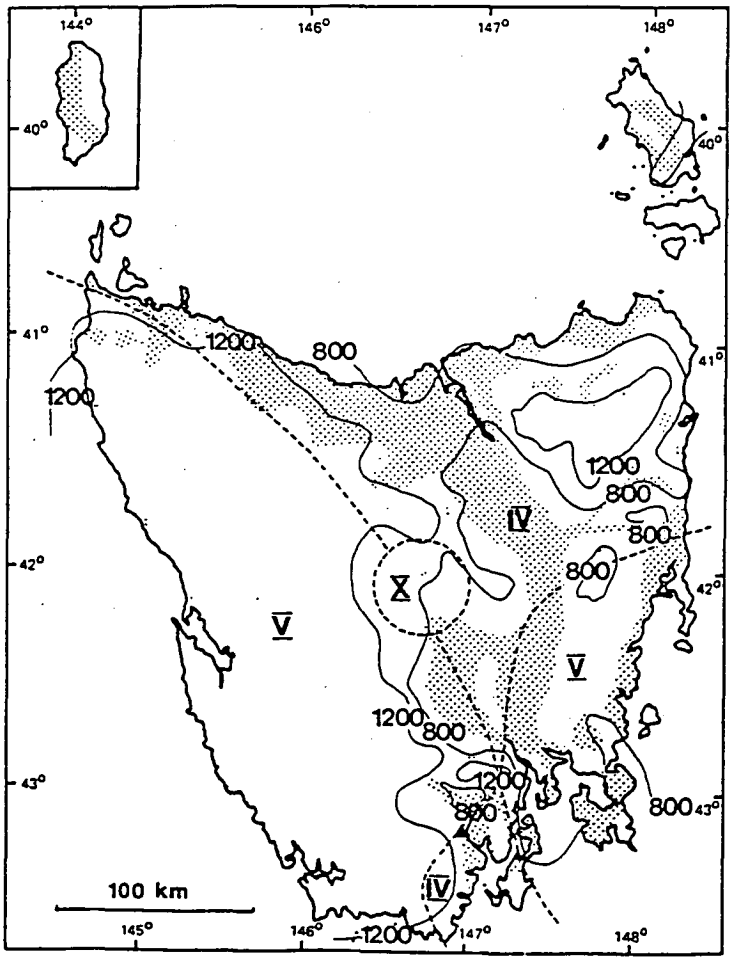
8.7. *Sminthurides* sp. 1



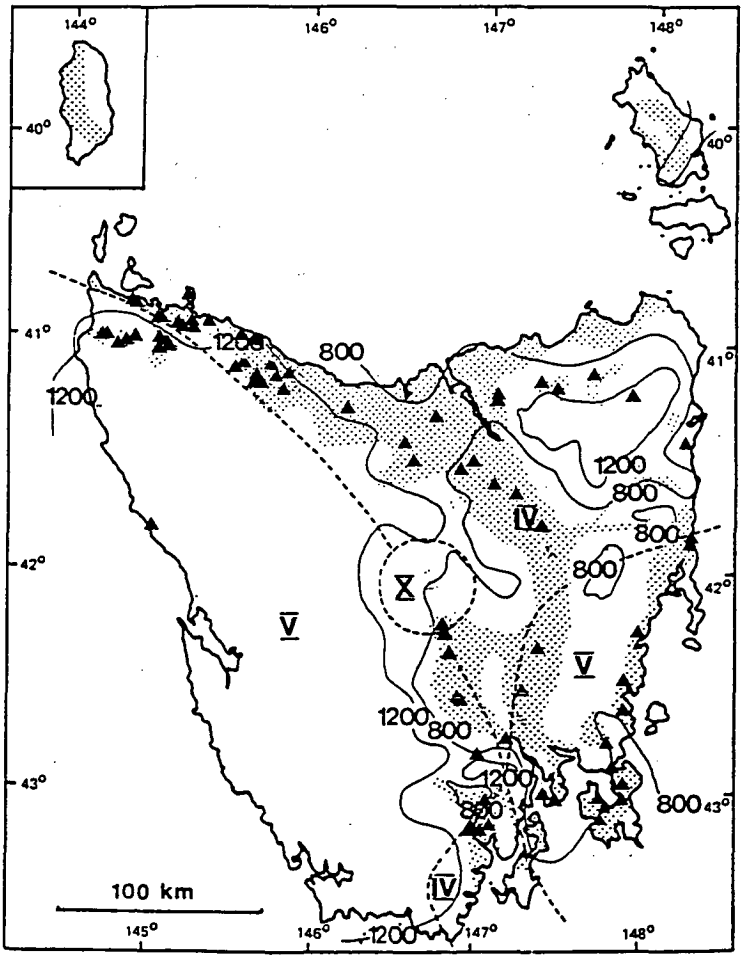
8.8. *K. australis*



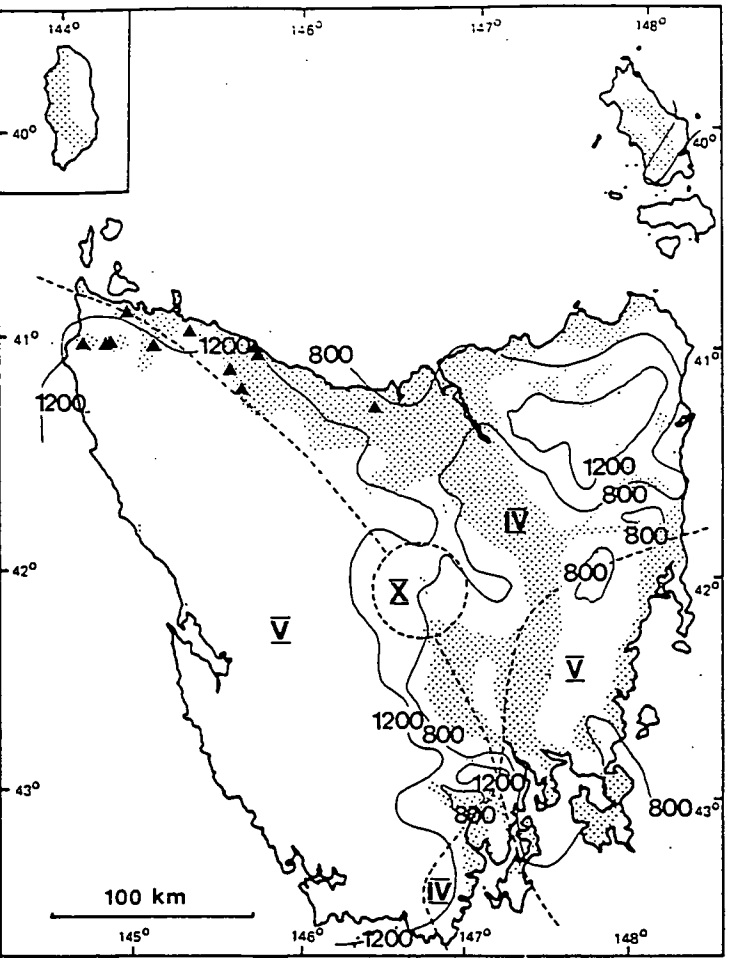
8.9. *K. mucina*



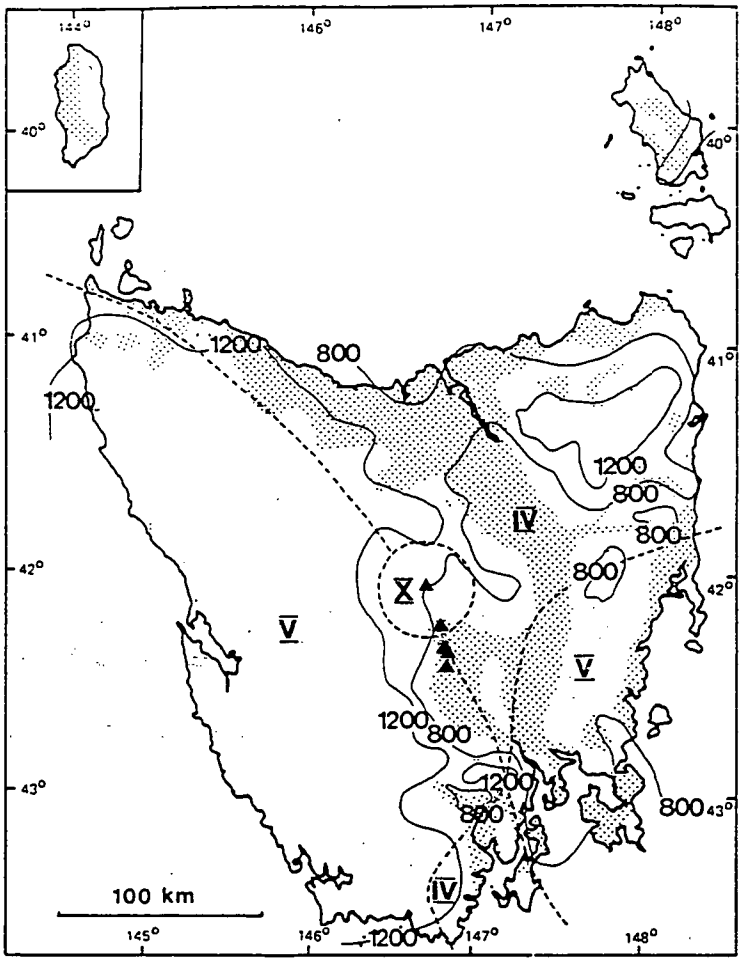
8.10. *K.* sp. cf. *obscura*



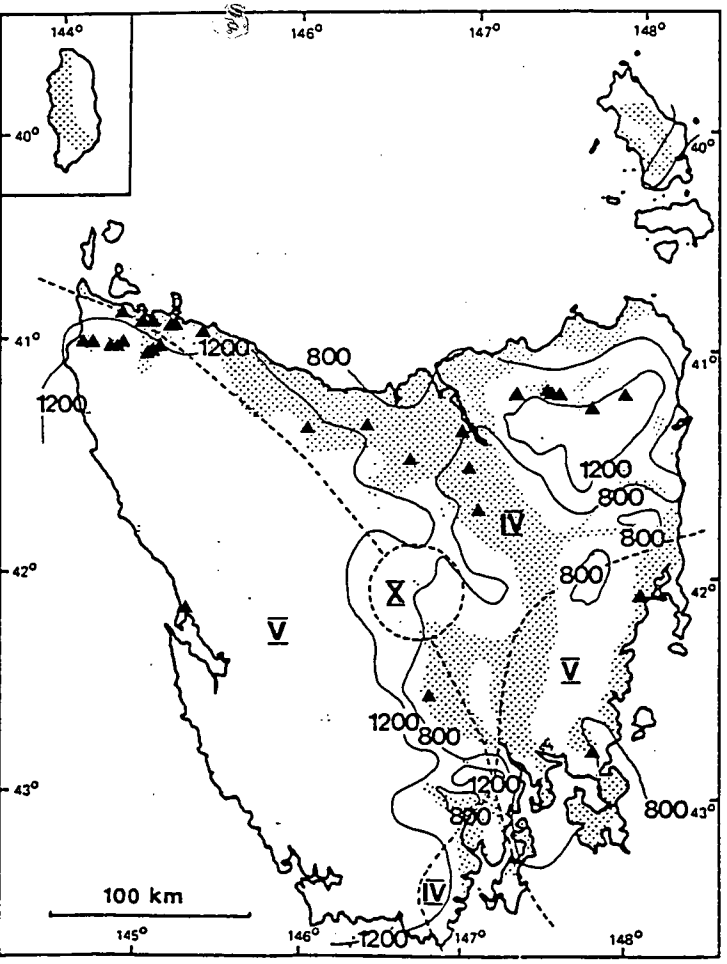
8.11. *K. oceanica* var. *schoetti*



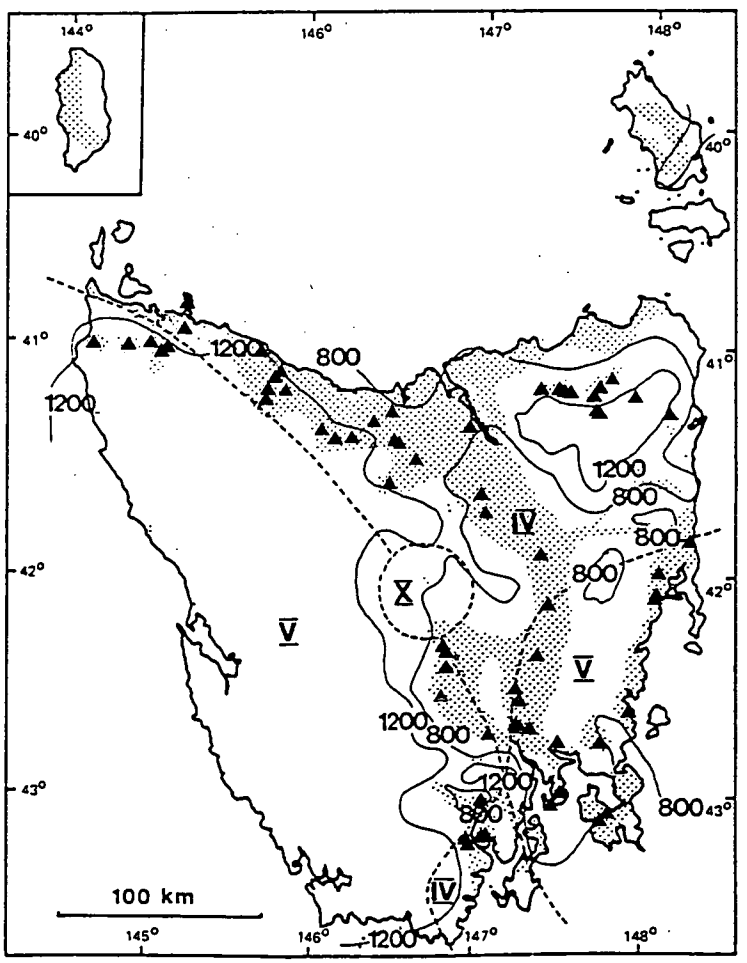
8.12. *K. ornata*



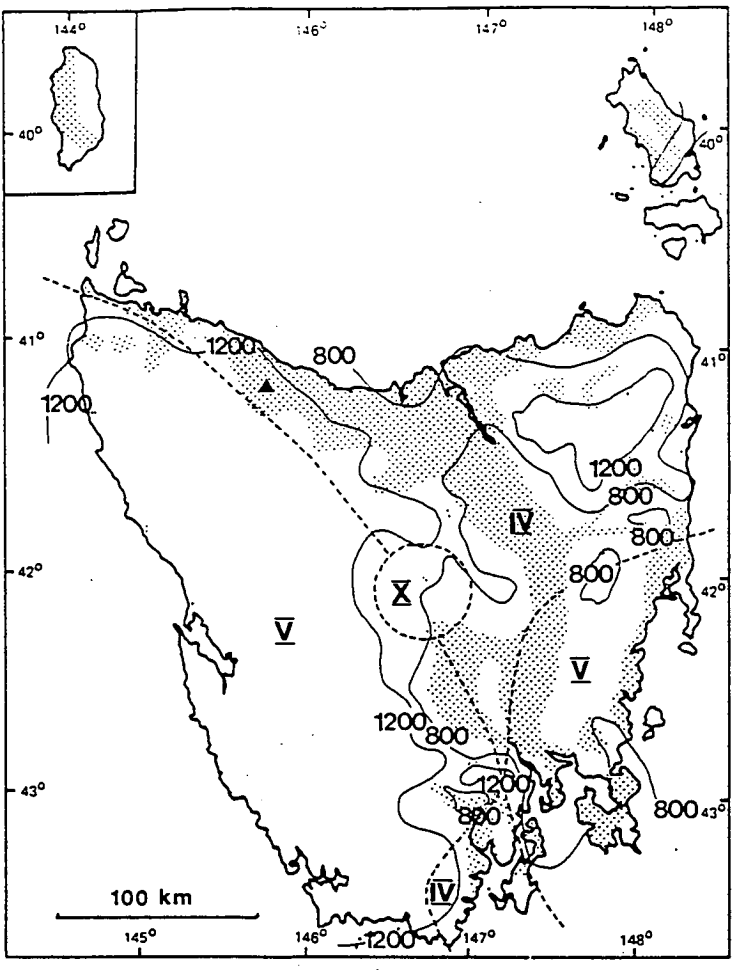
8.13. *K. pescotii*



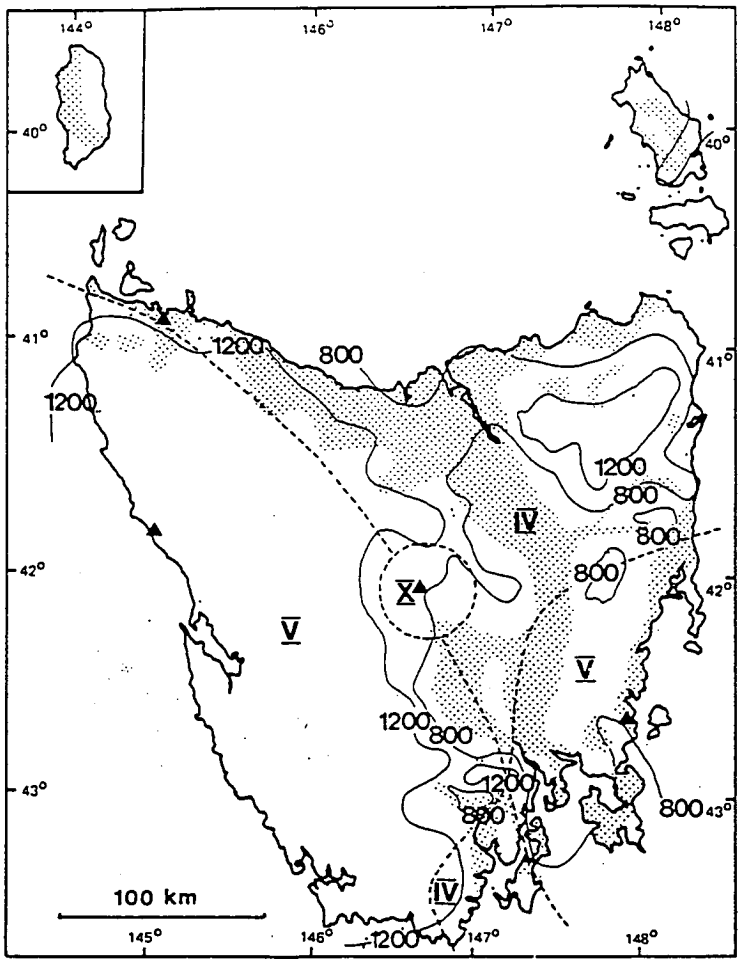
8.14. *Katianna* sp. 1



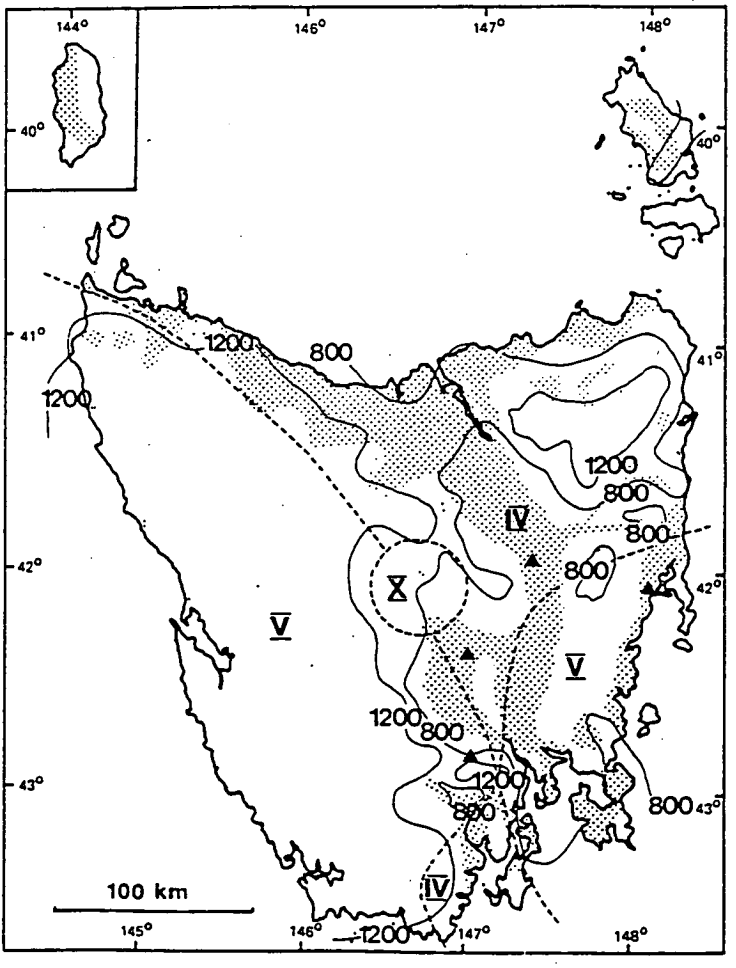
8.15. *S. elegans*



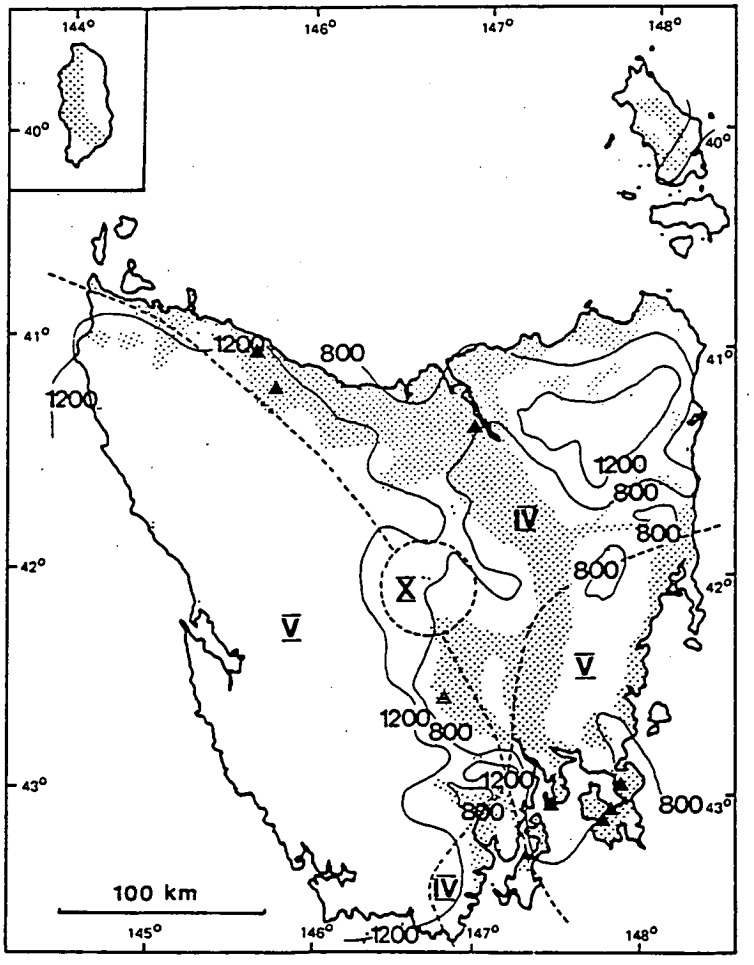
8.16. *S. mime*



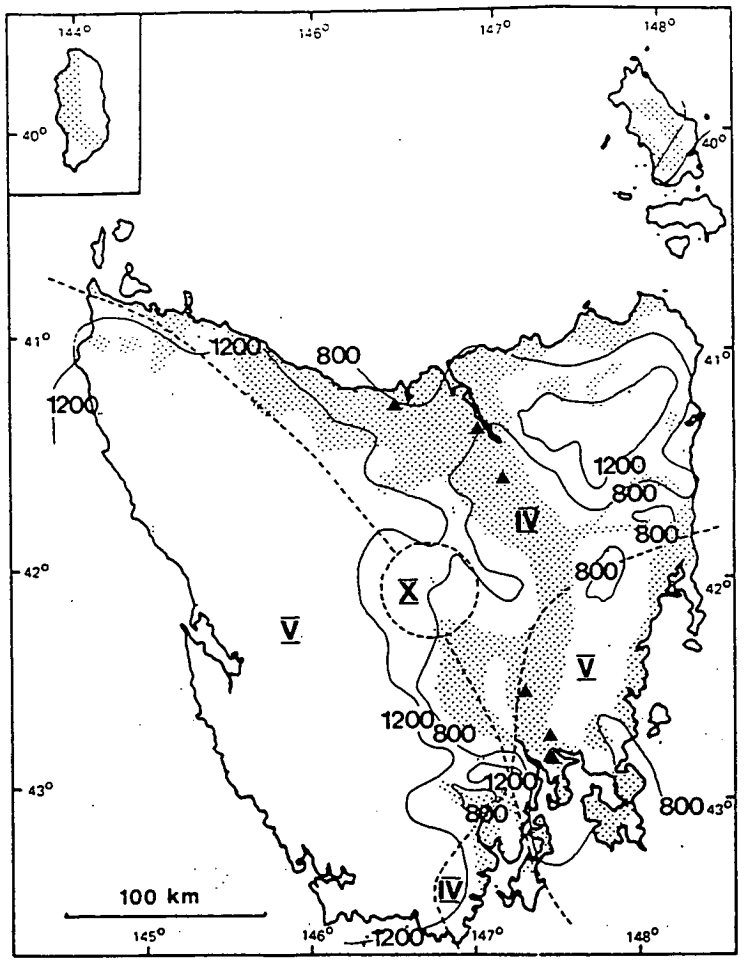
8.17. *S. tuberculatus*



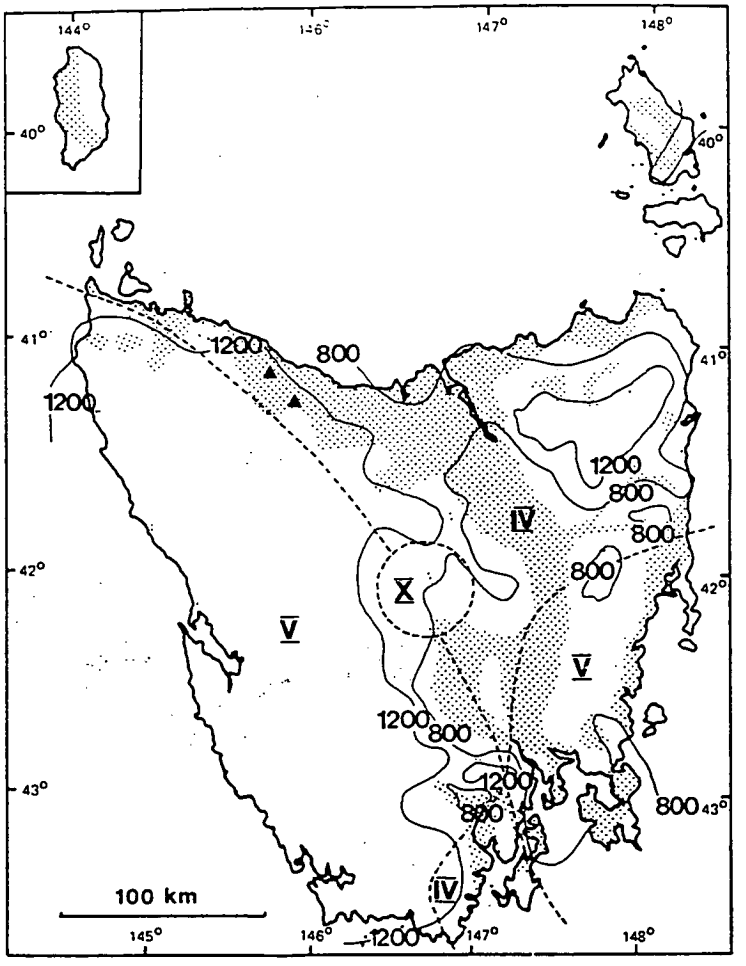
8.18. *Sminthurinus* sp. 1



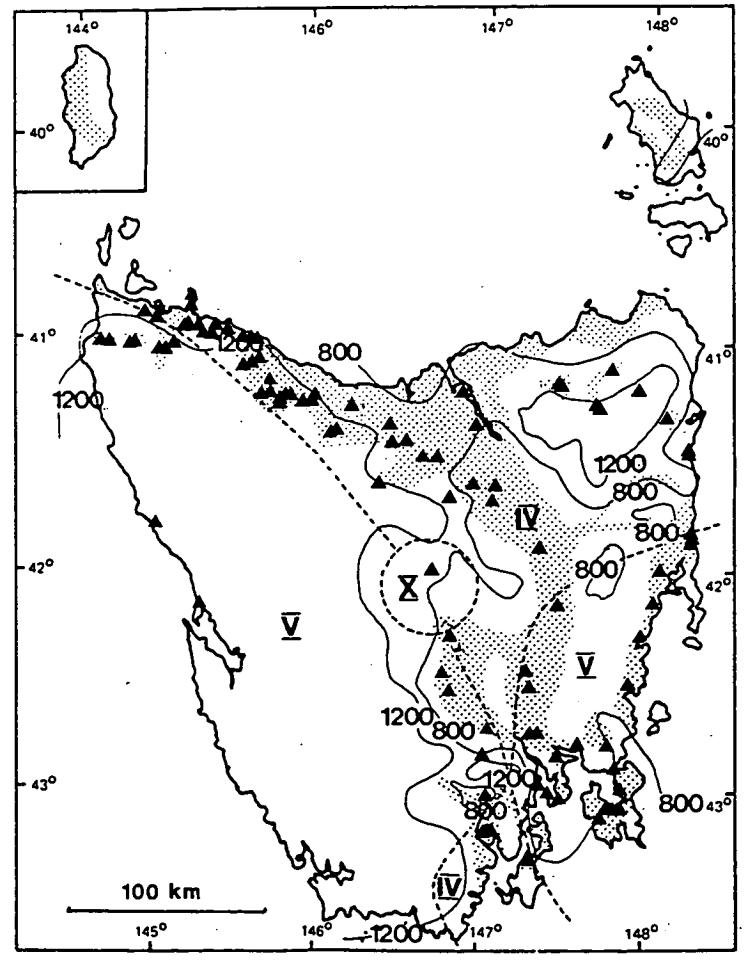
8.19. *D. sulphureus mediterraneus*



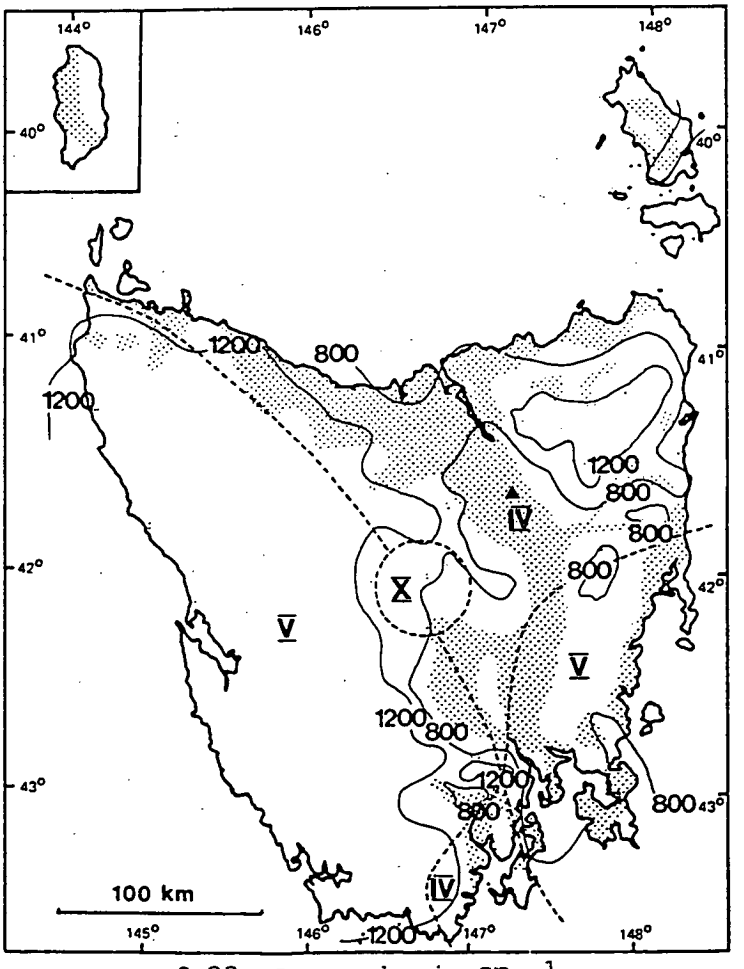
8.20. *P. quinquefasciatus*



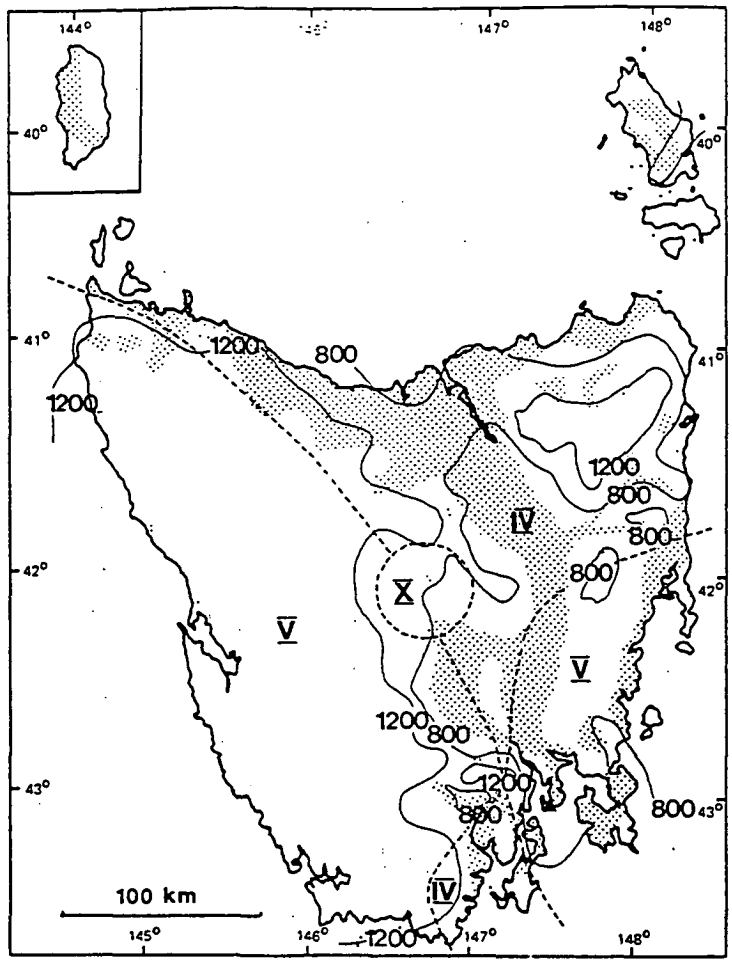
8.21. *B. hortensis*



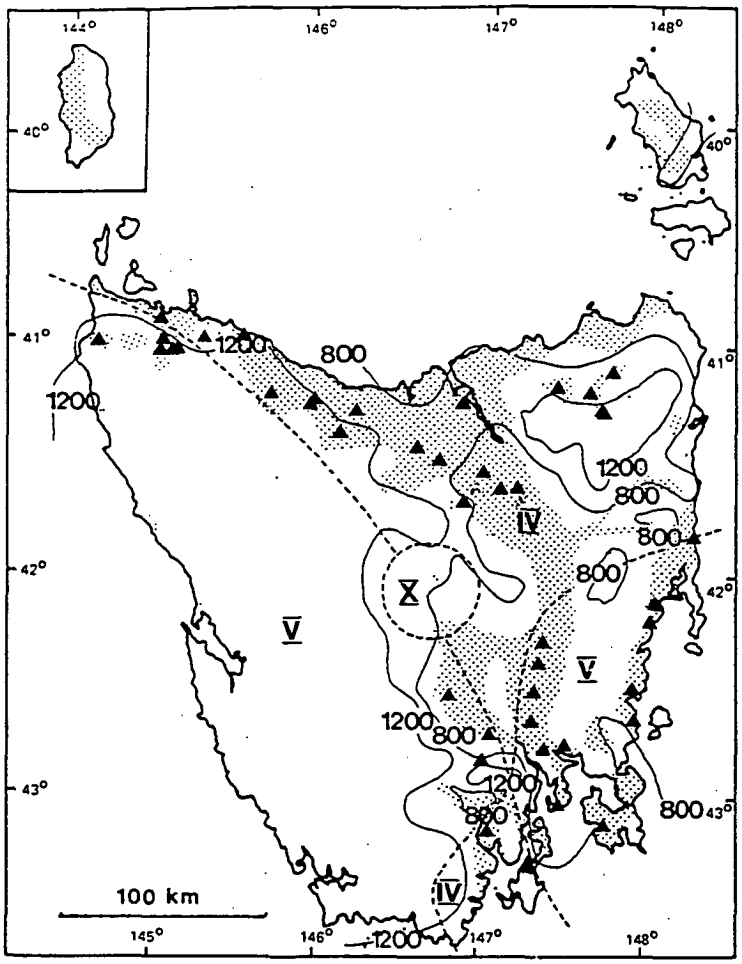
8.22. *B. viridescens*



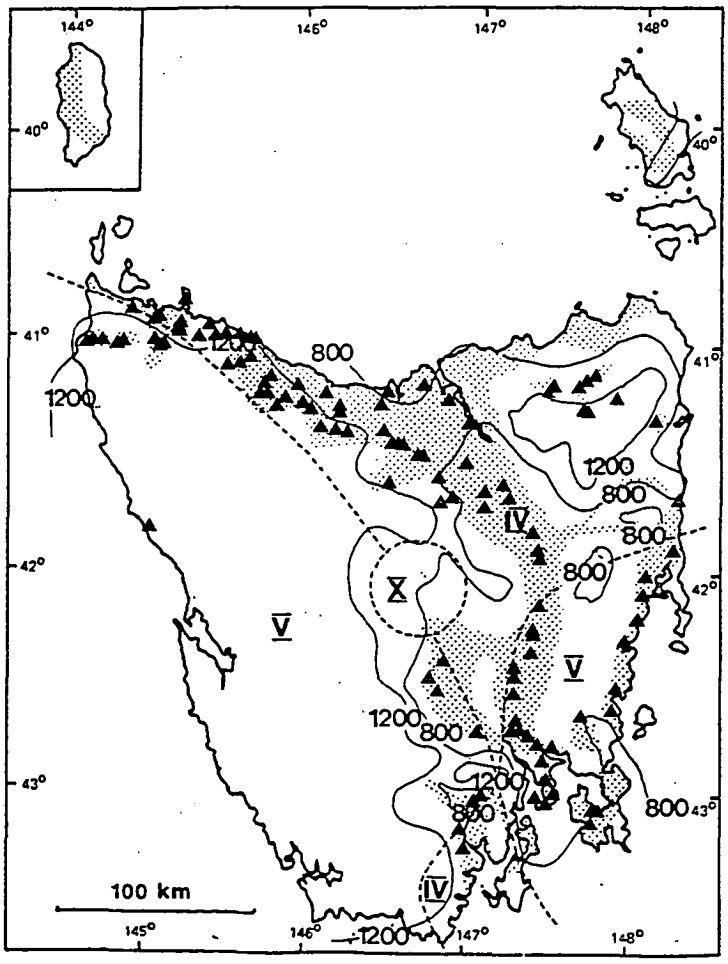
8.23. *Corynephoria* sp. 1



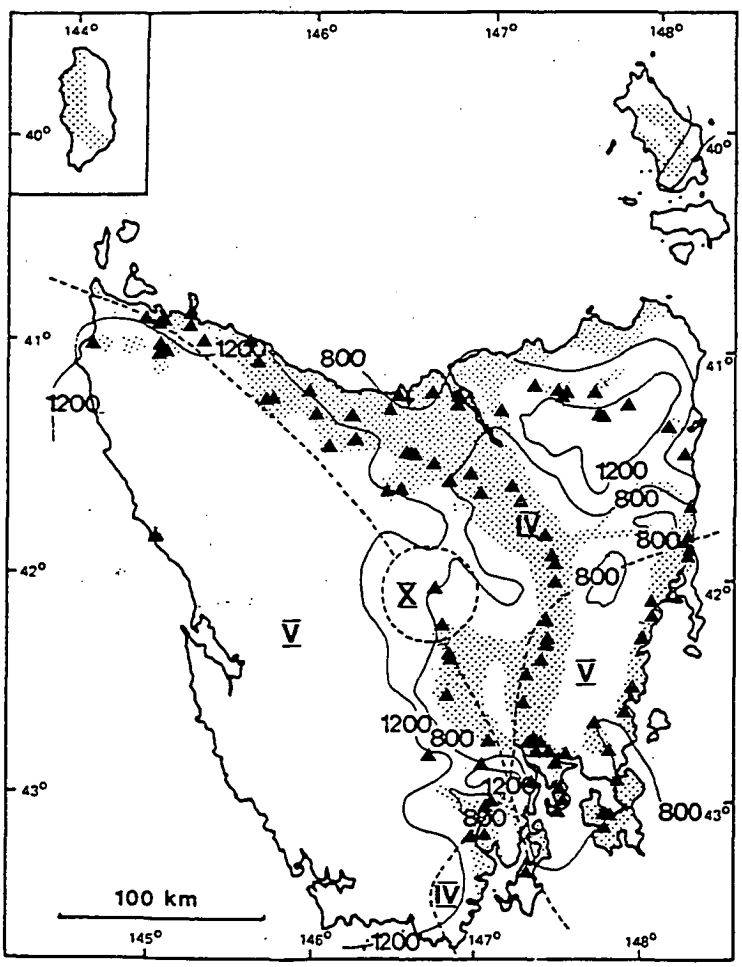
8.24. *A. echidnus*



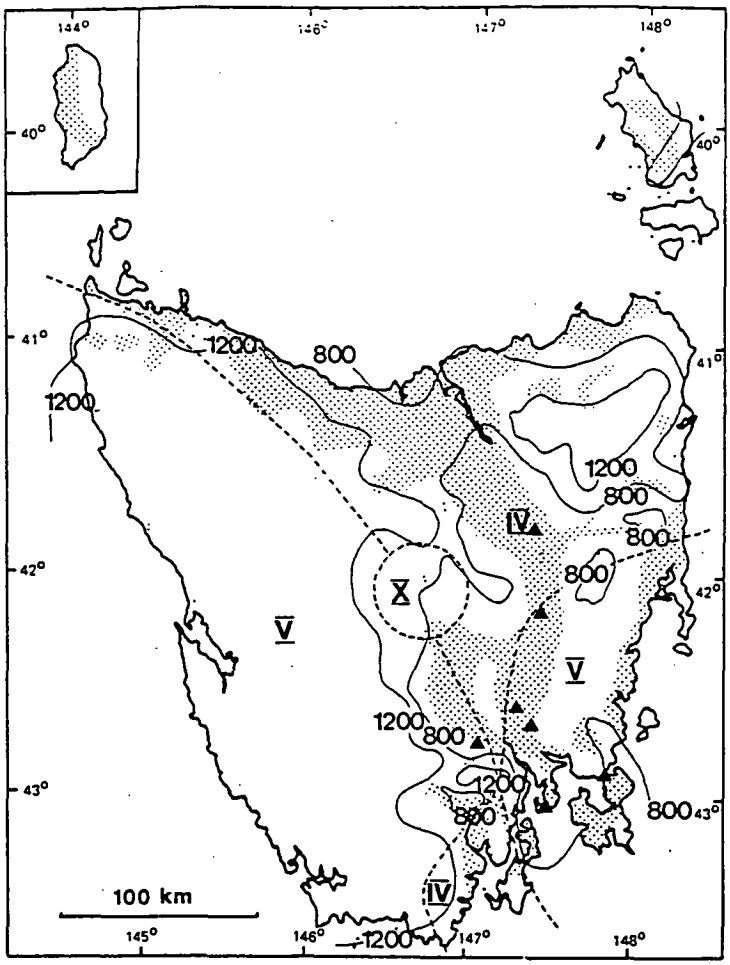
8.25. *E. lanuginosa*



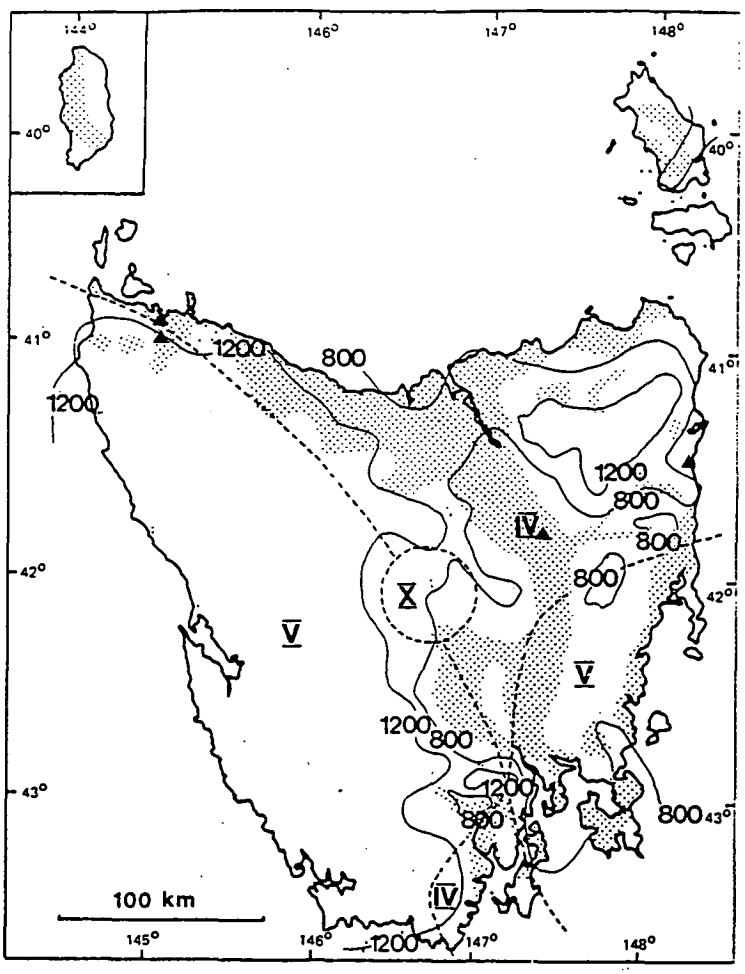
8.26. *E. marginata*



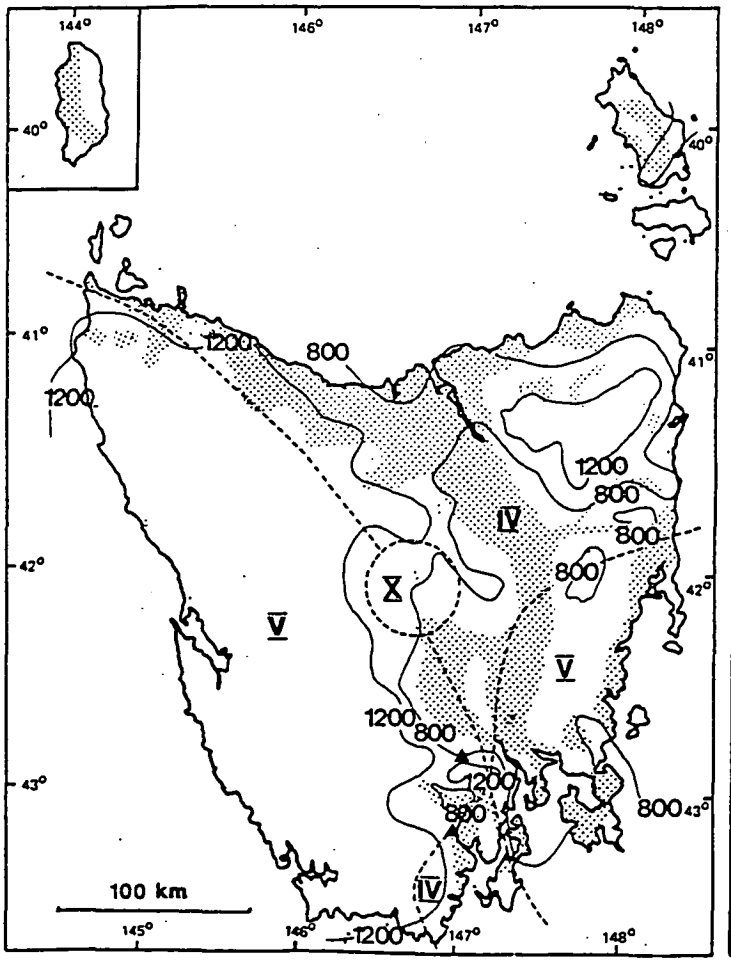
8.27. *E. multifasciata*



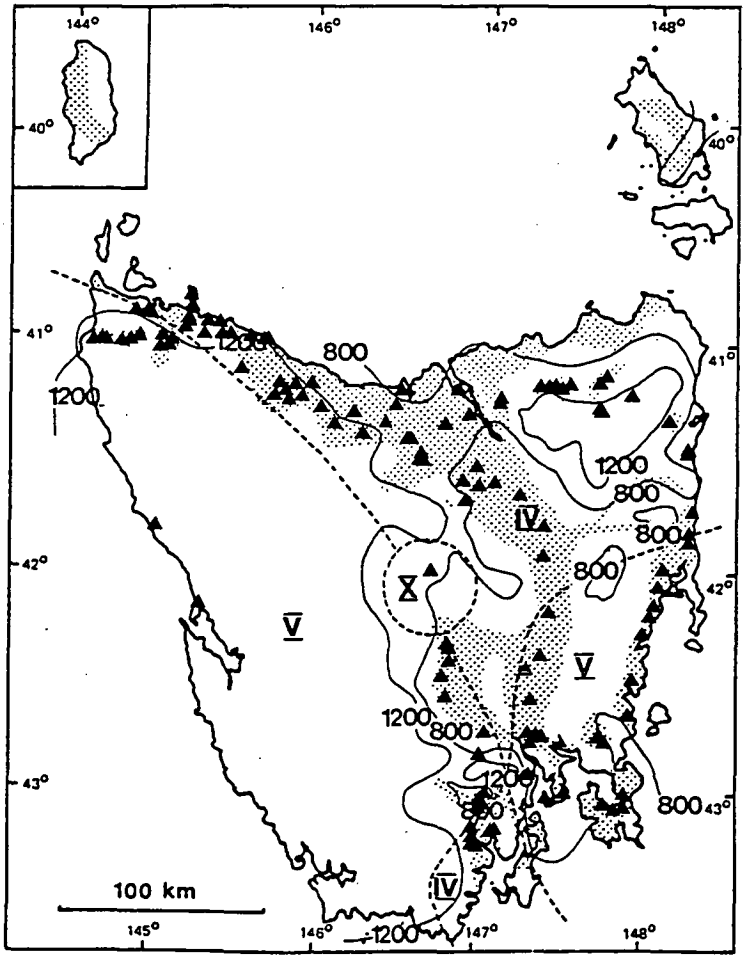
8.28. *E. unostrigata*



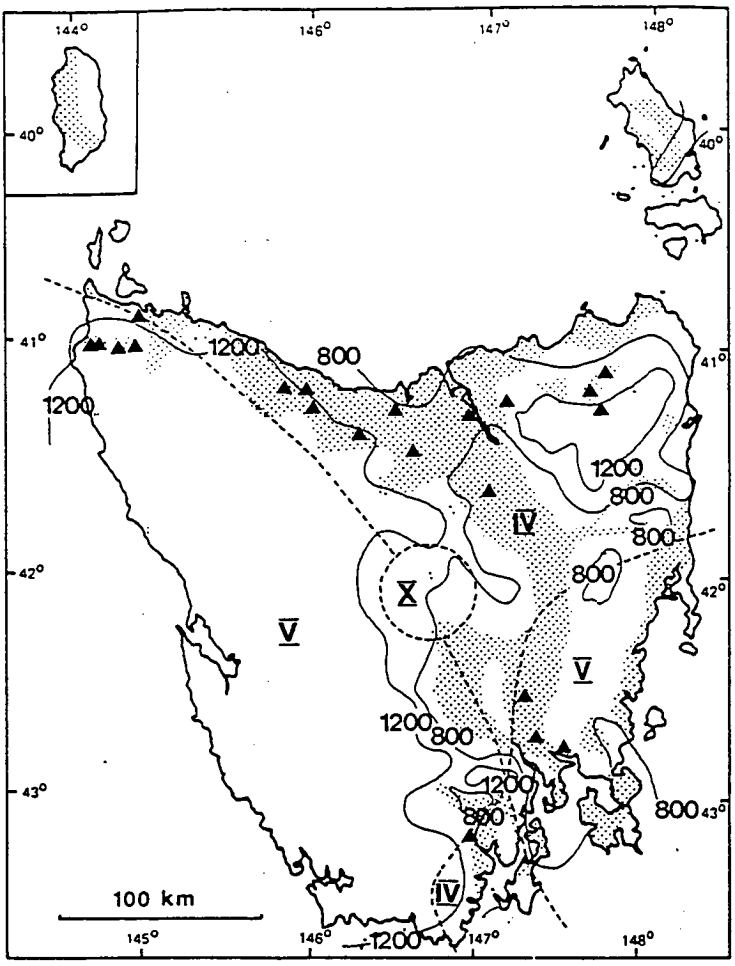
8.29. *Lepidocyrtoides* sp. 1



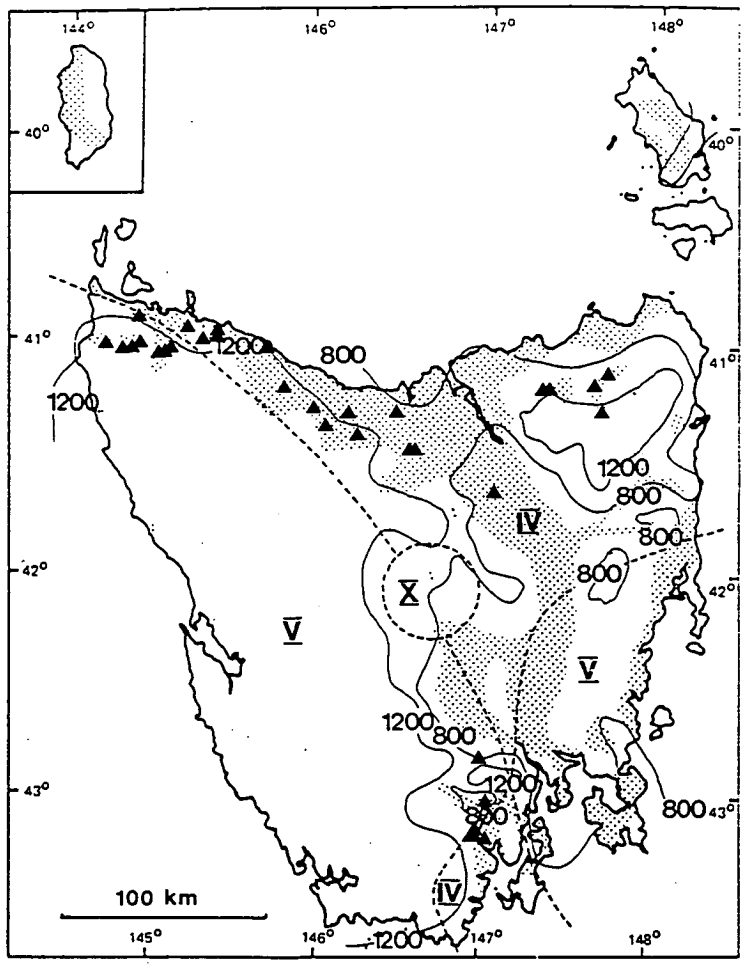
8.30. *Lepidocyrtus* sp. 1



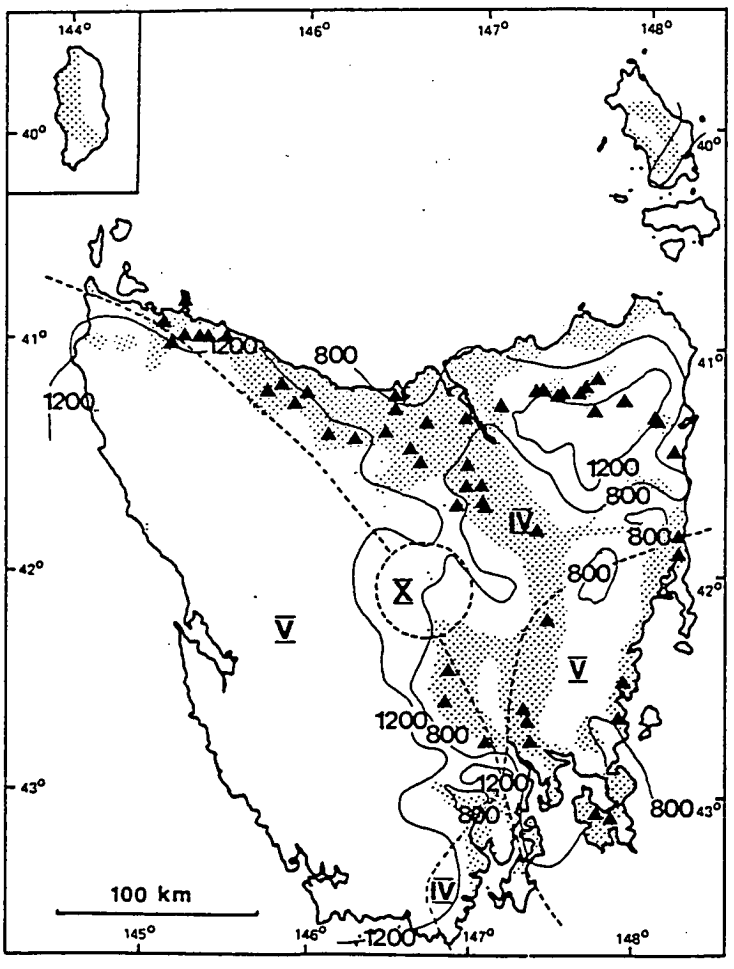
8.31. *I. palustris*



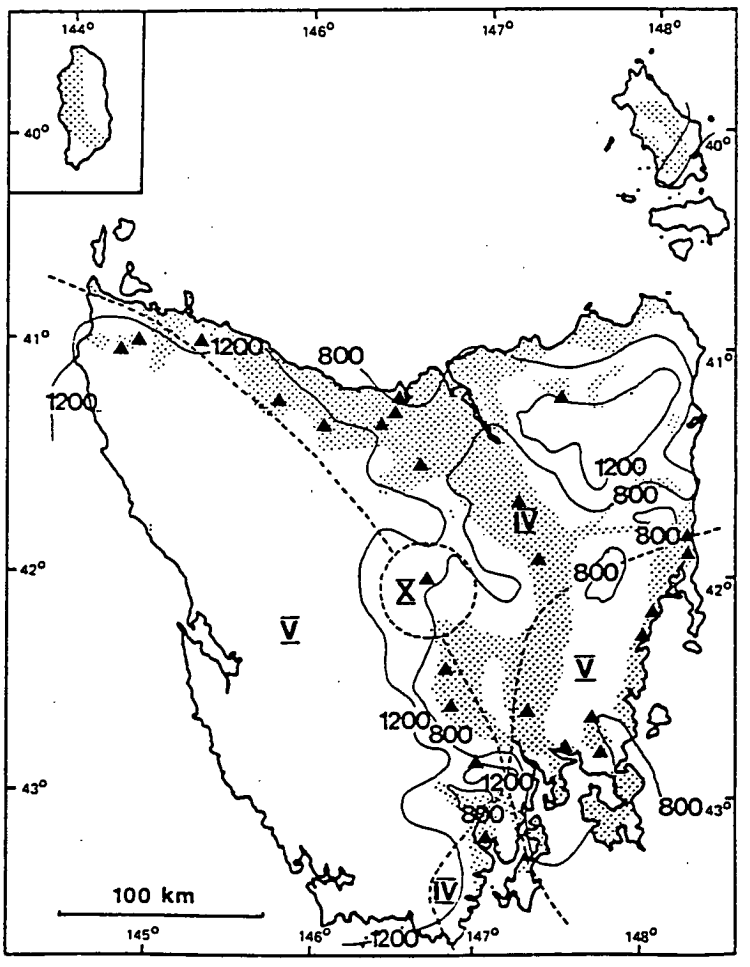
8.32. *I. notabilis*



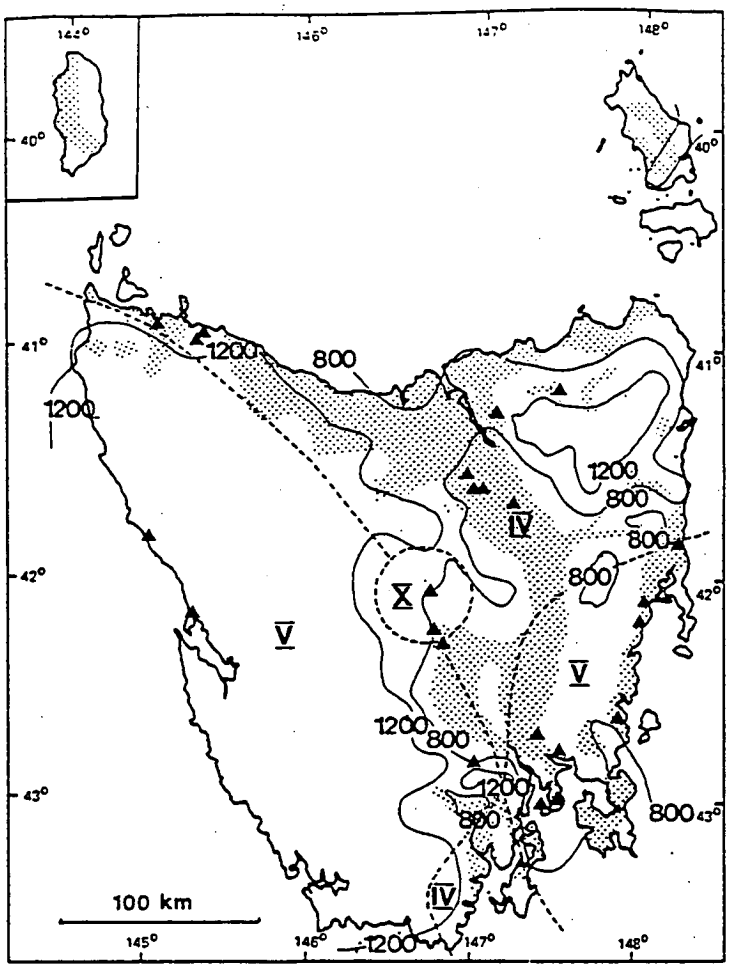
8.33. *I. tigrina*



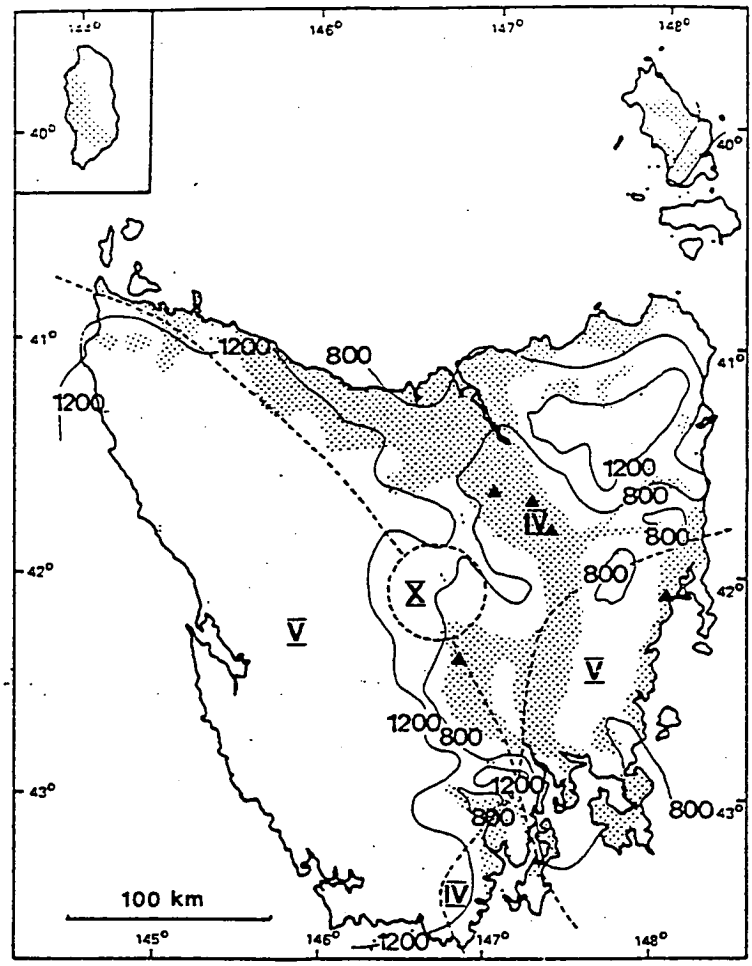
8.34. *C. thermophilus*



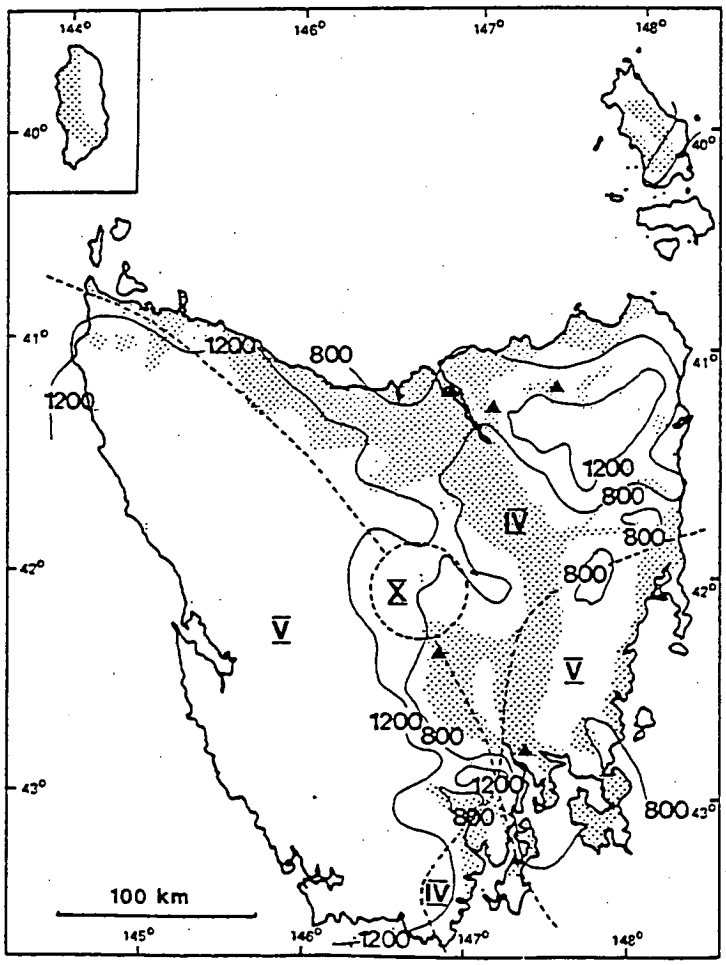
8.35. *H. denticulata*



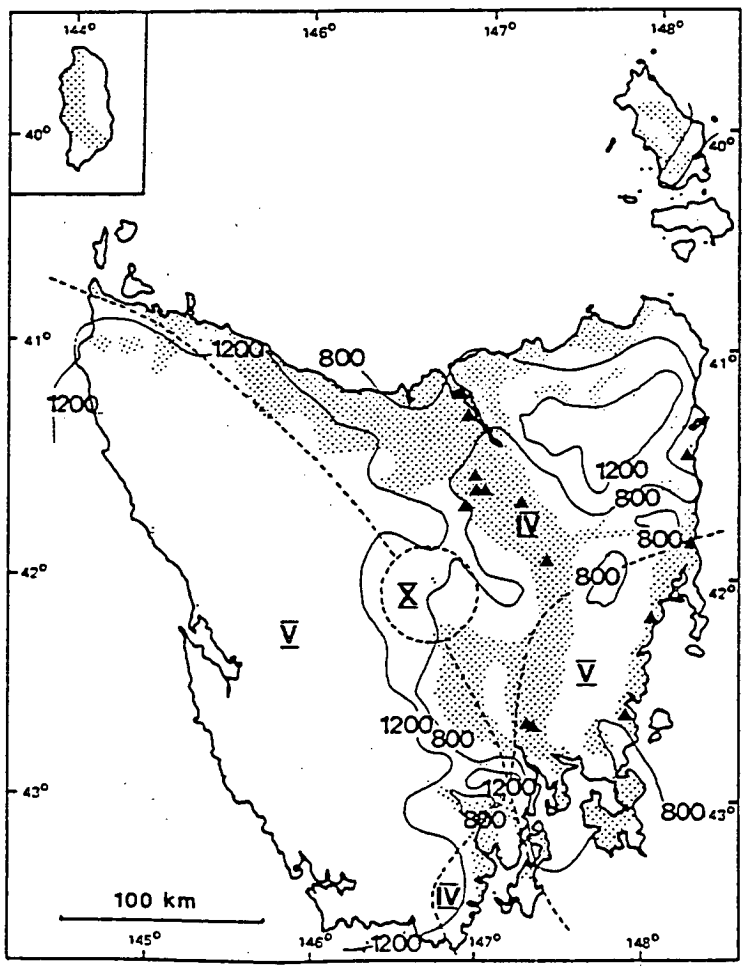
8.36. *H.* sp. cf. *engadinensis*



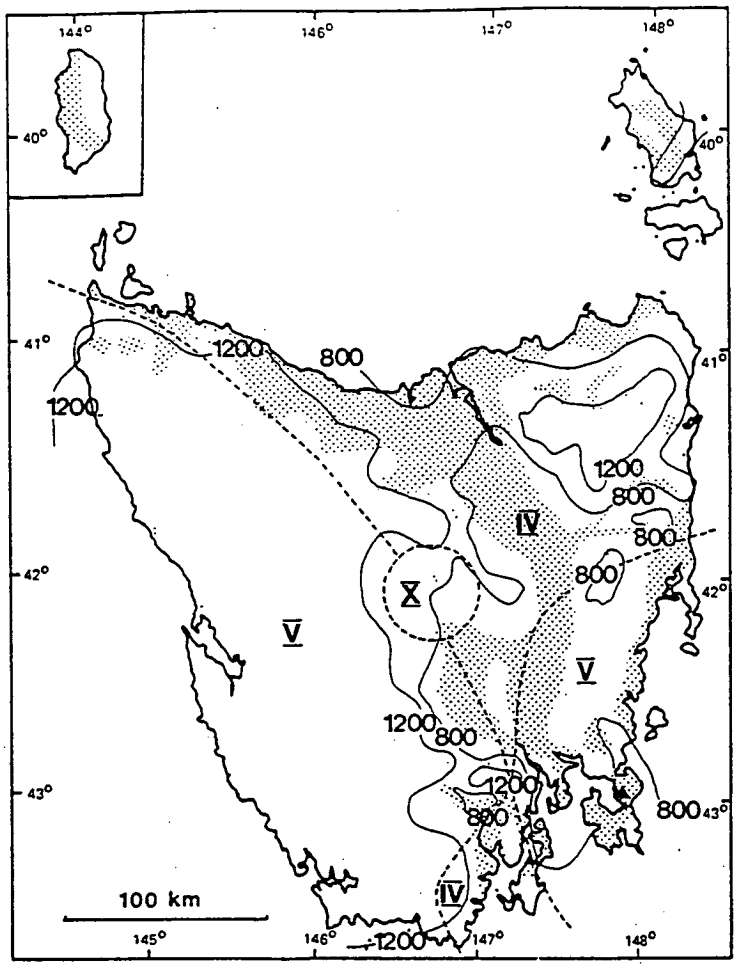
8.37. *H. gibbosa*



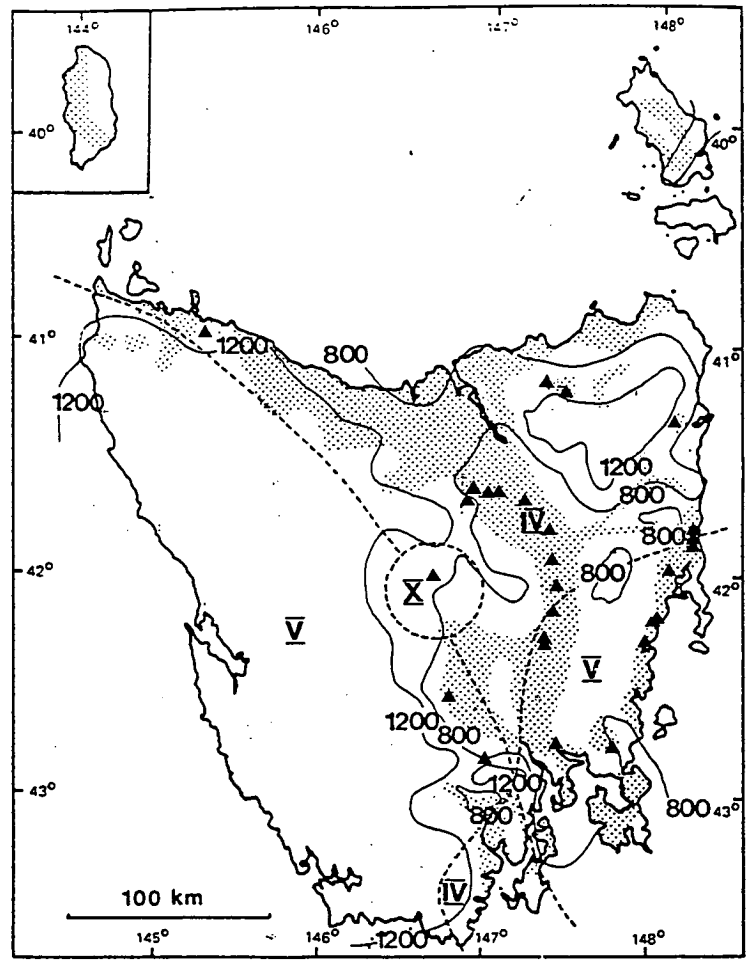
8.38. *H. assimilis*



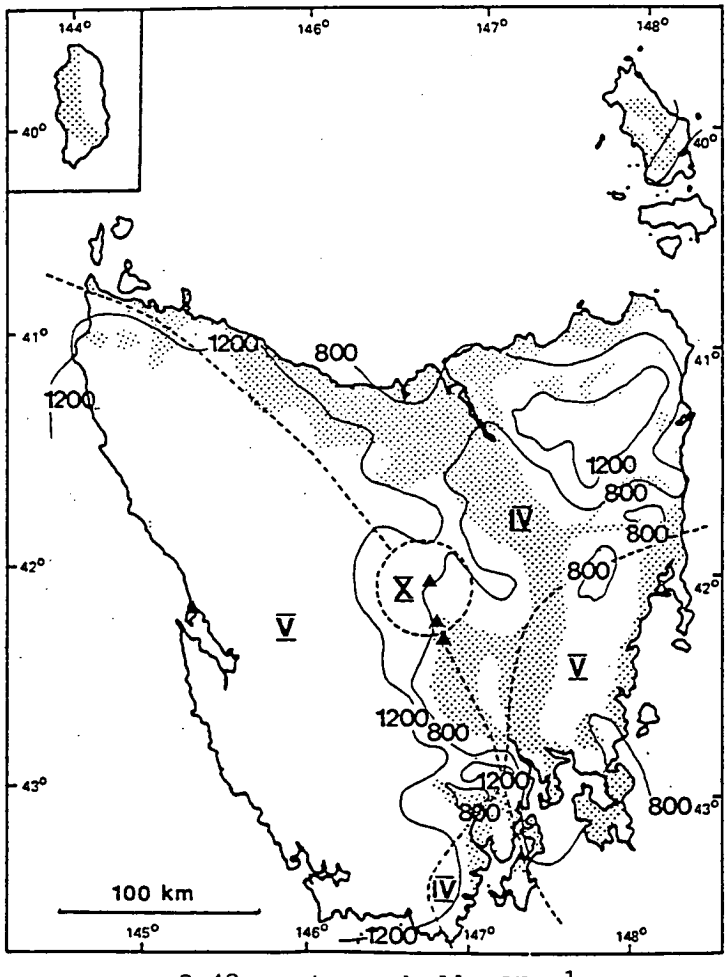
8.39. *H. manubrialis*



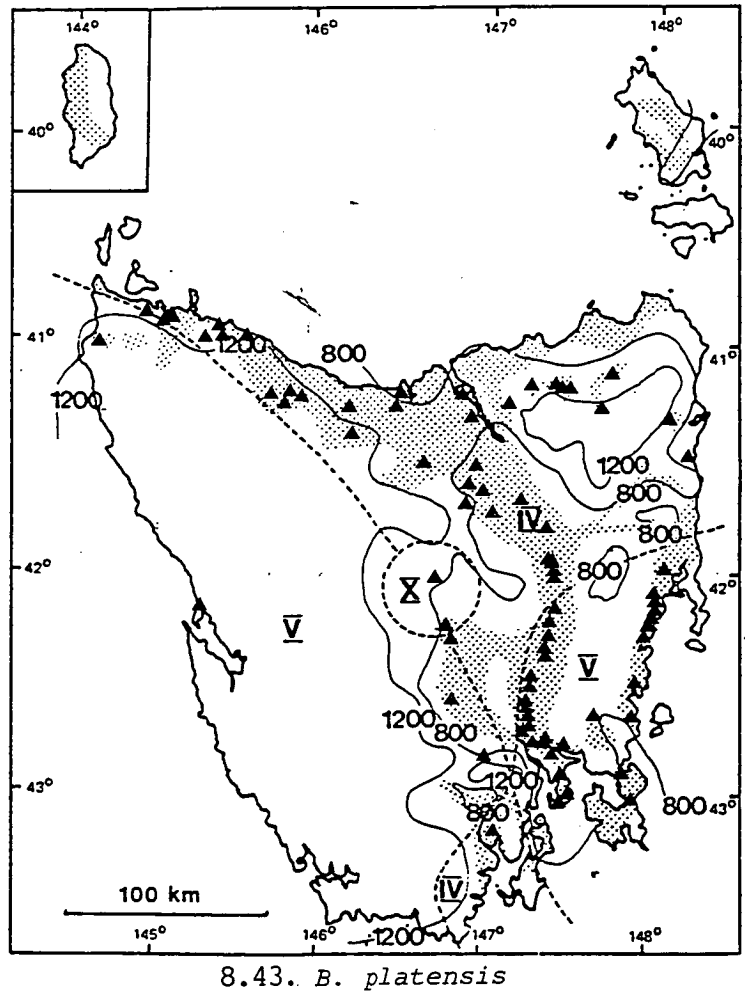
8.40. *H. purpurescens*



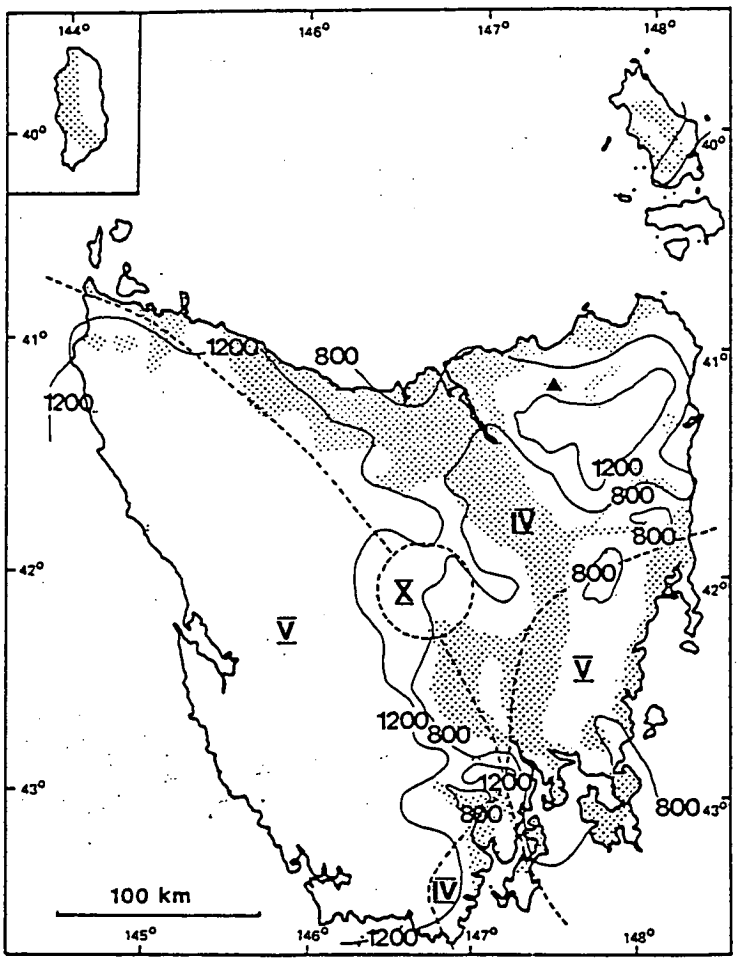
8.41. *H. vernalis*



8.42. *Triacanthella* sp. 1

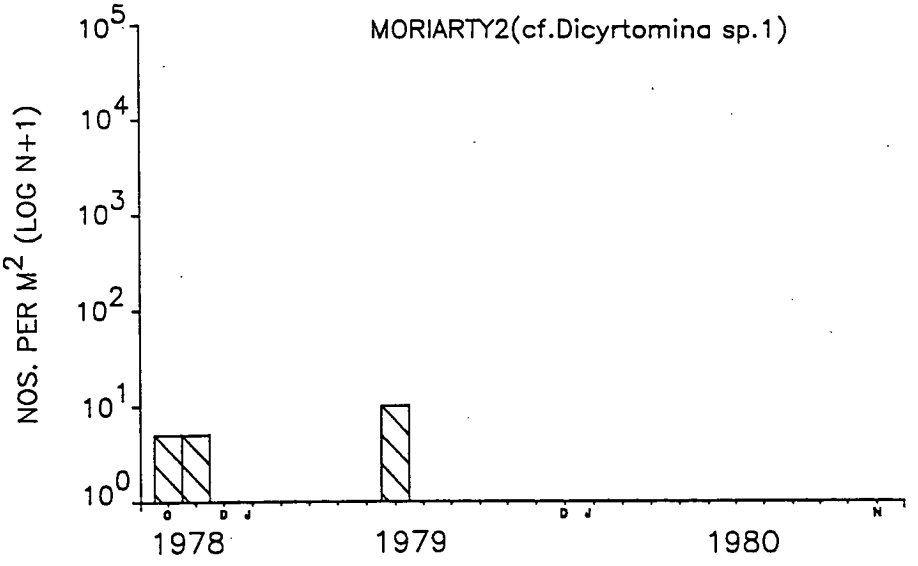


8.43. *B. platensis*

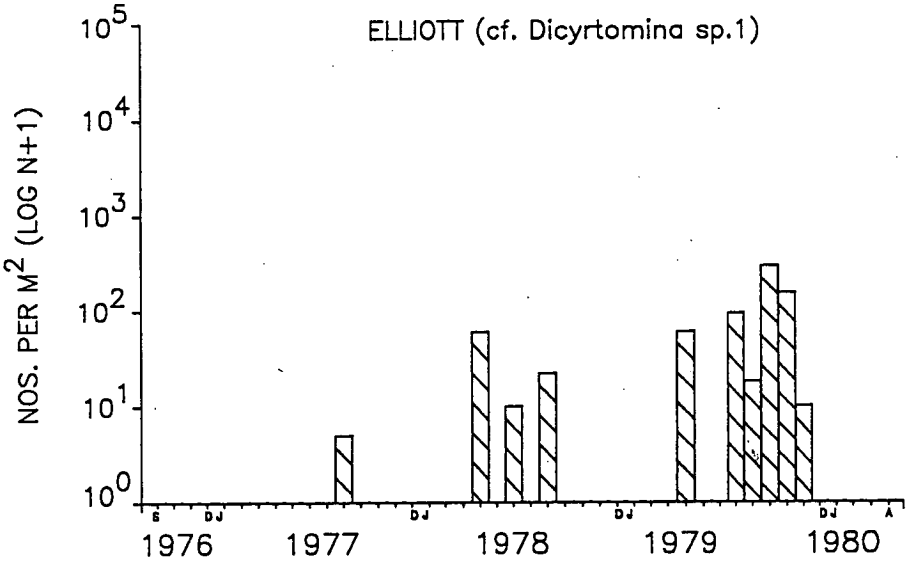


8.44. *N. muscorum*

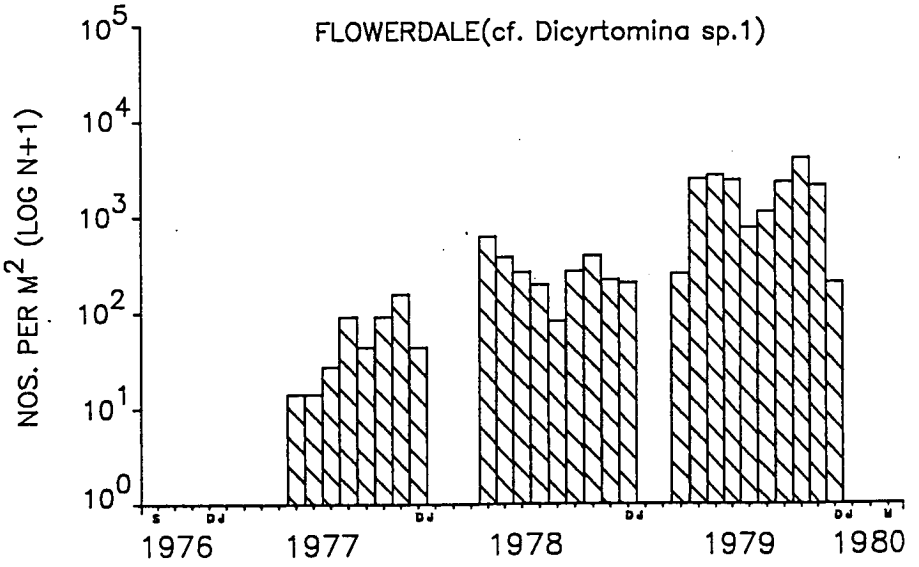
Figs 8.45 - 8.101 Monthly variations in populations of individual collembolan species at monitored high rainfall (wet) sites at Moriarty 1 (September 1976 - August 1978), Moriarty 2 (October 1978 - November 1980), Elliott Research Station (Elliott) (September 1976 - April 1980), Flowerdale (September 1976 - March 1980) and for B. platensis at Moriarty 3 (November 1981 - October 1982).


MORIARTY2(cf.Dicyrtomina sp.1)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1978
1979
1980

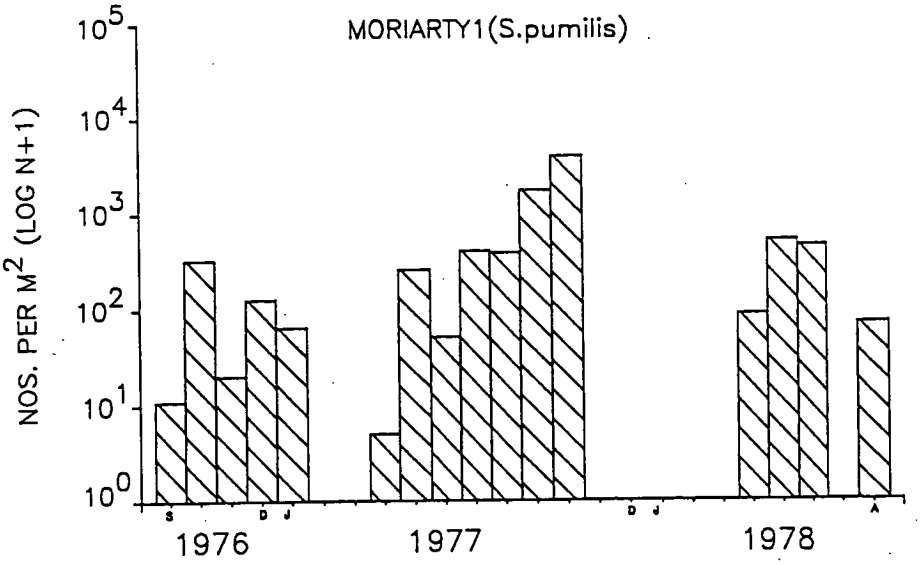
45


ELLIOTT (cf. Dicyrtomina sp.1)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

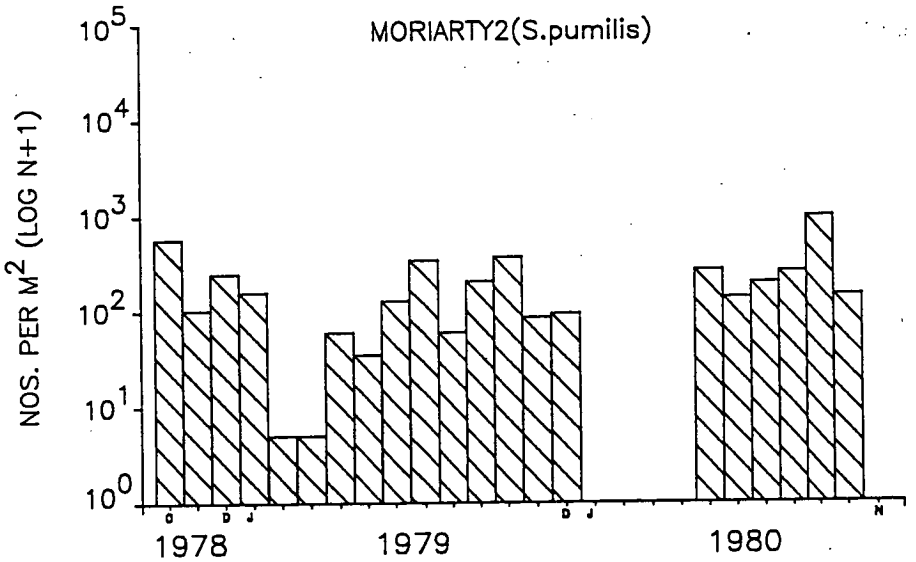
46


FLOWERDALE(cf. Dicyrtomina sp.1)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

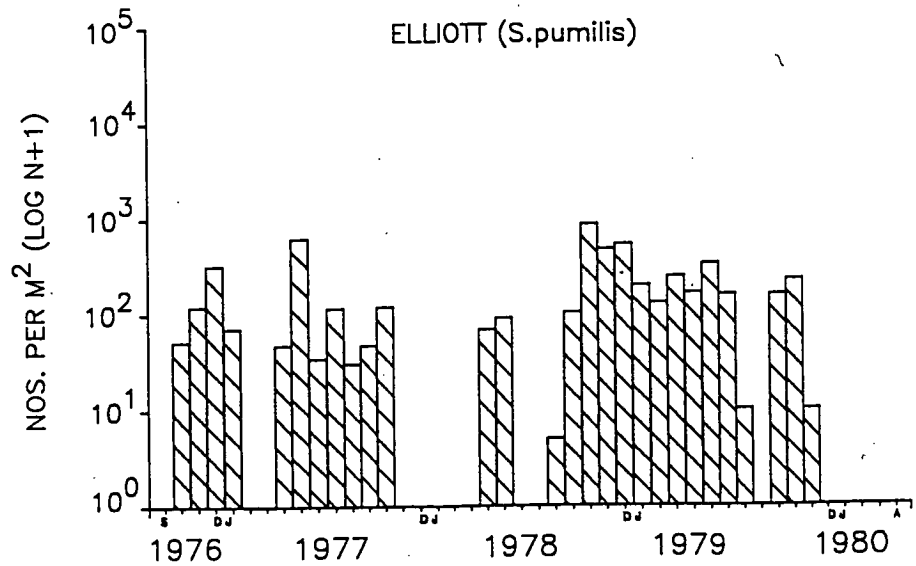
47


MORIARTY1(S.pumilis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D J
D J
A
1976
1977
1978

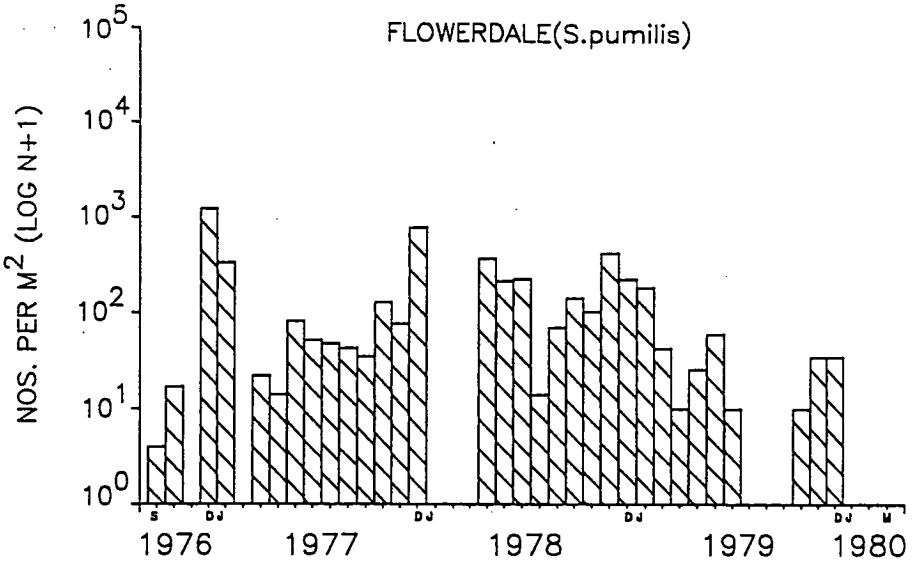
48


MORIARTY2(S.pumilis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D J
D J
N
1978
1979
1980

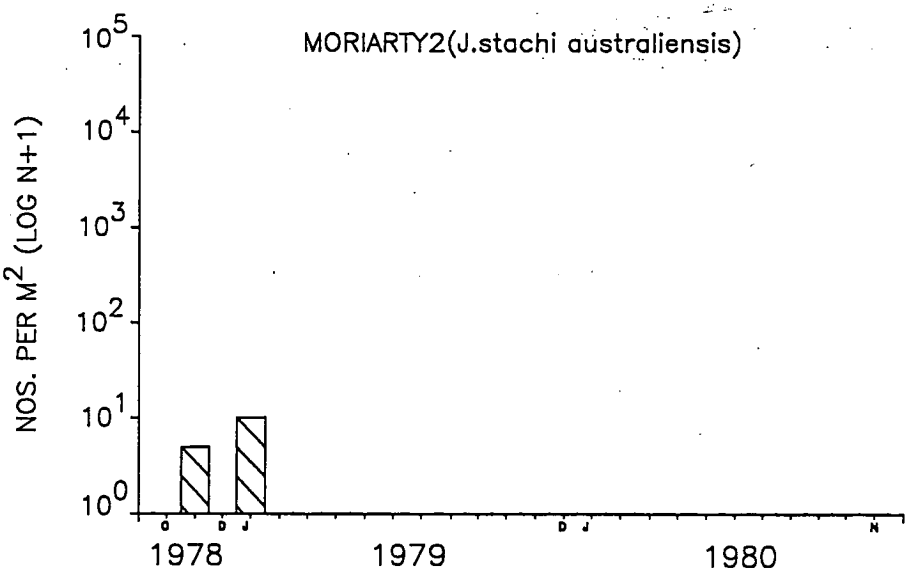
49


ELLIOTT (S.pumilis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

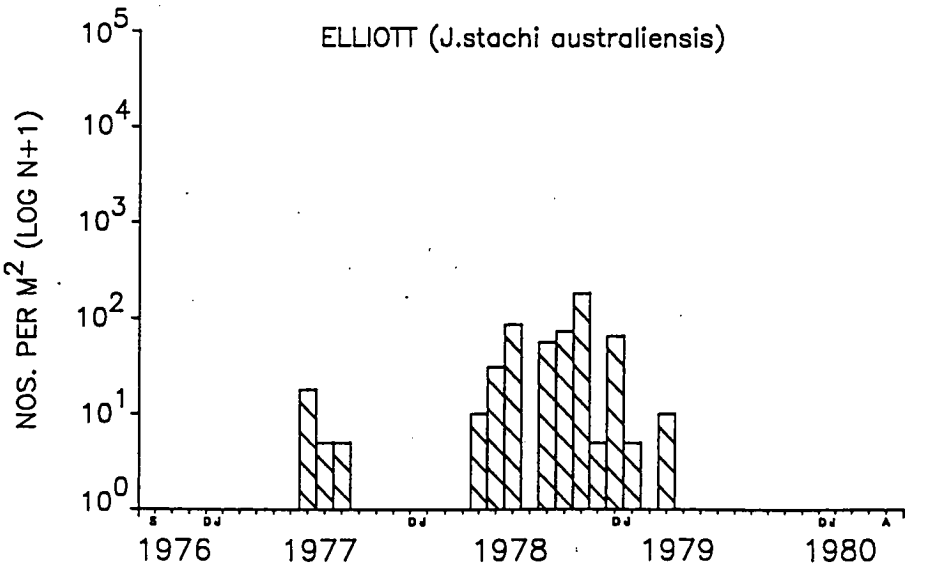
50


FLOWERDALE(S.pumilis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
M
1976
1977
1978
1979
1980

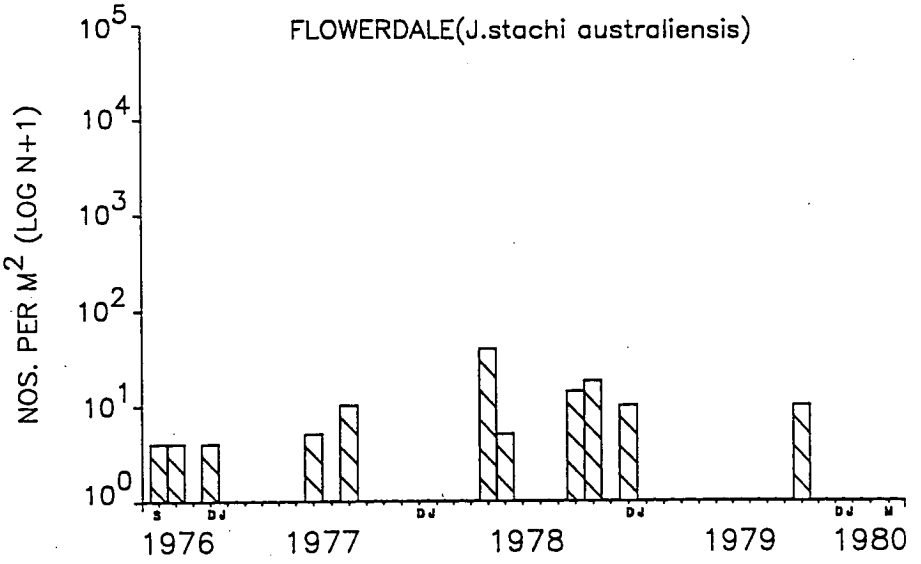
51


MORIARTY2(J.stachi australiensis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
D
J
D
J
N
1978
1979
1980

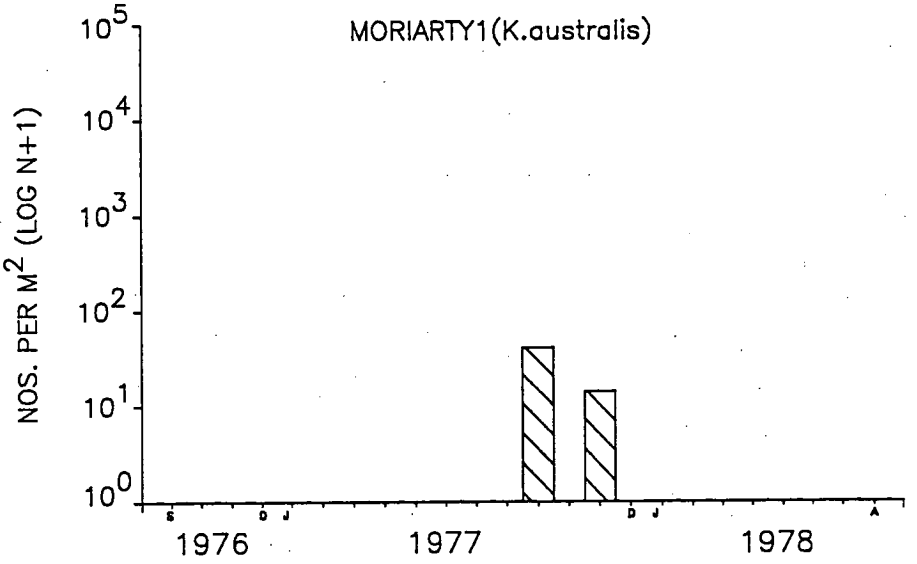
52


ELLIOTT (J.stachi australiensis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

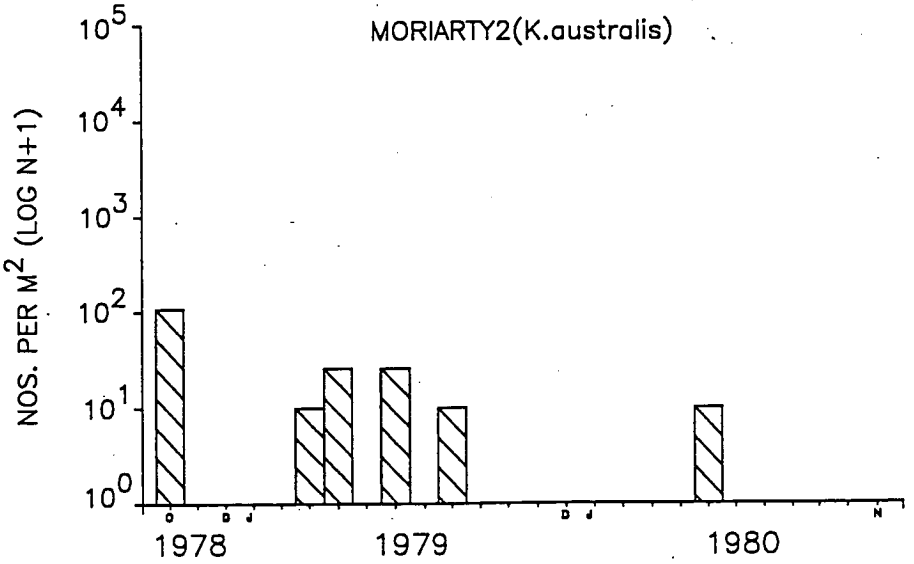
53


FLOWERDALE(J.stachi australiensis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D J
D J
D J
D J
M
1976
1977
1978
1979
1980

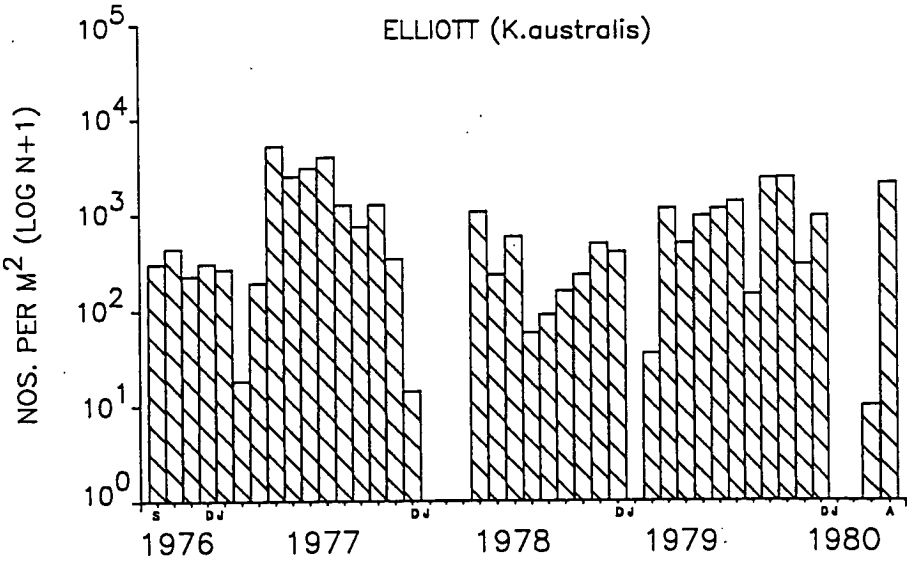
54


MORIARTY1(K.australis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
O J
D J
A
1976
1977
1978

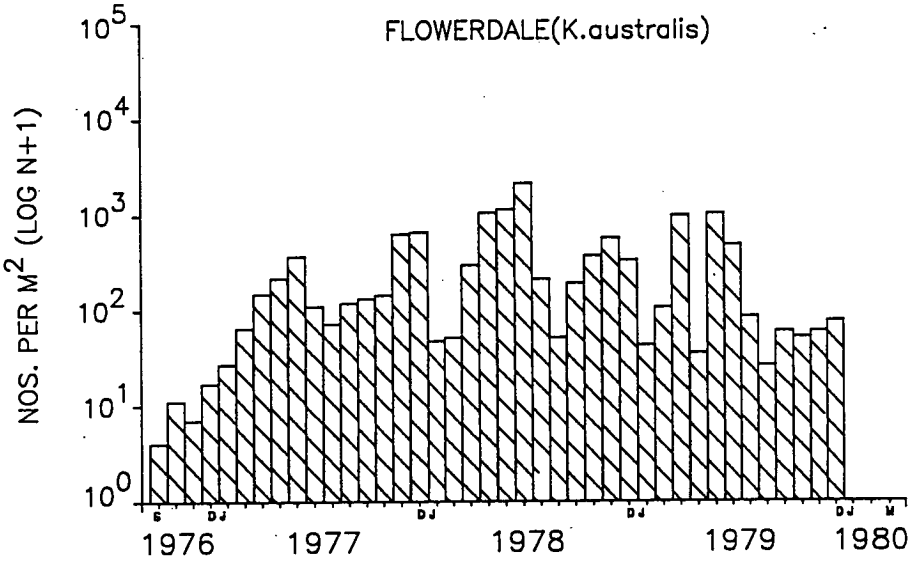
55


MORIARTY2(K.australis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D J
D J
N
1978
1979
1980

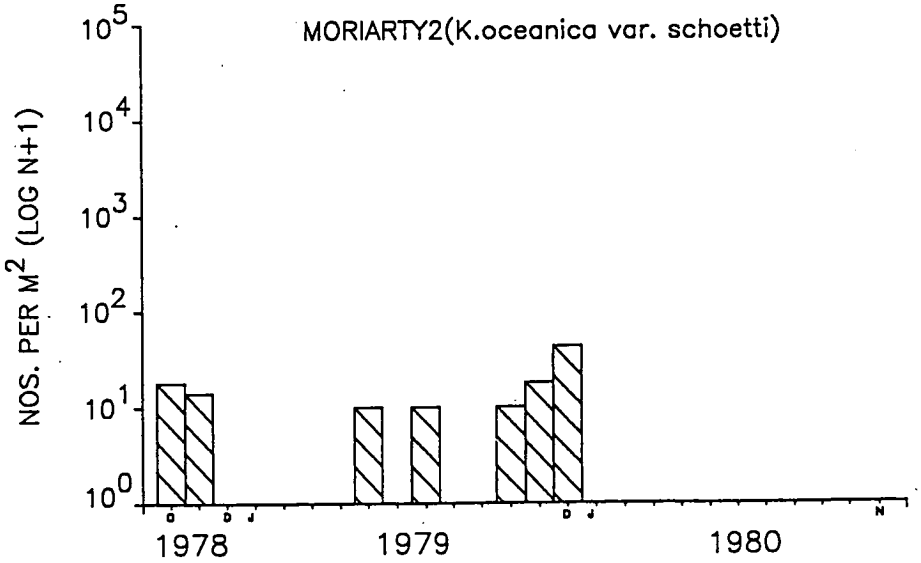
56


ELLIOTT (K.australis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

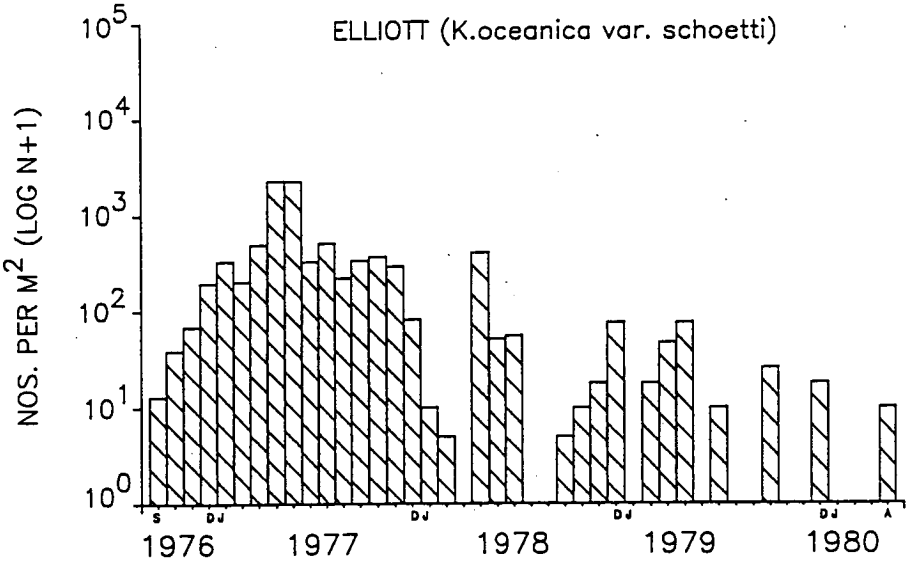
57


FLOWERDALE(K.australis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

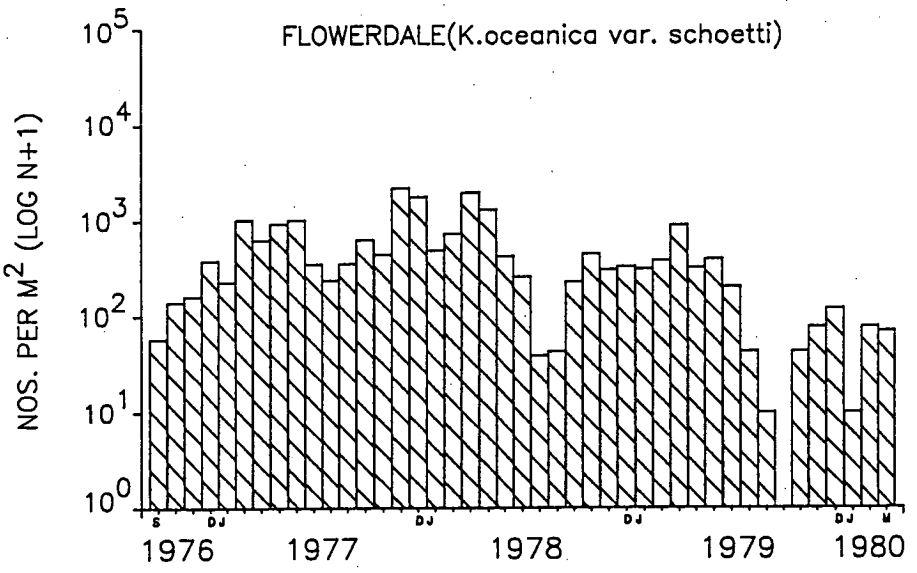
58


MORIARTY2(K.oceanica var. schoetti)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1978
1979
1980

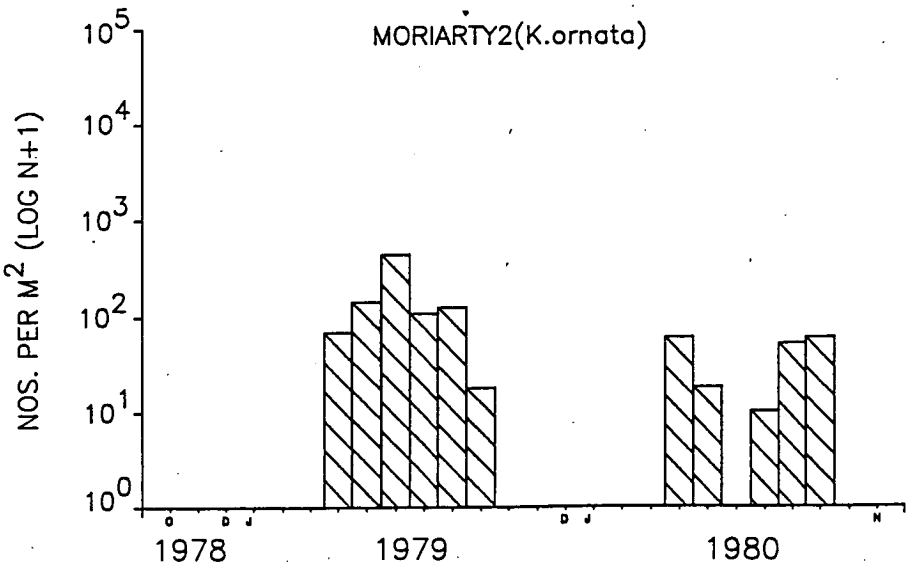
59


ELLIOTT (K.oceanica var. schoetti)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

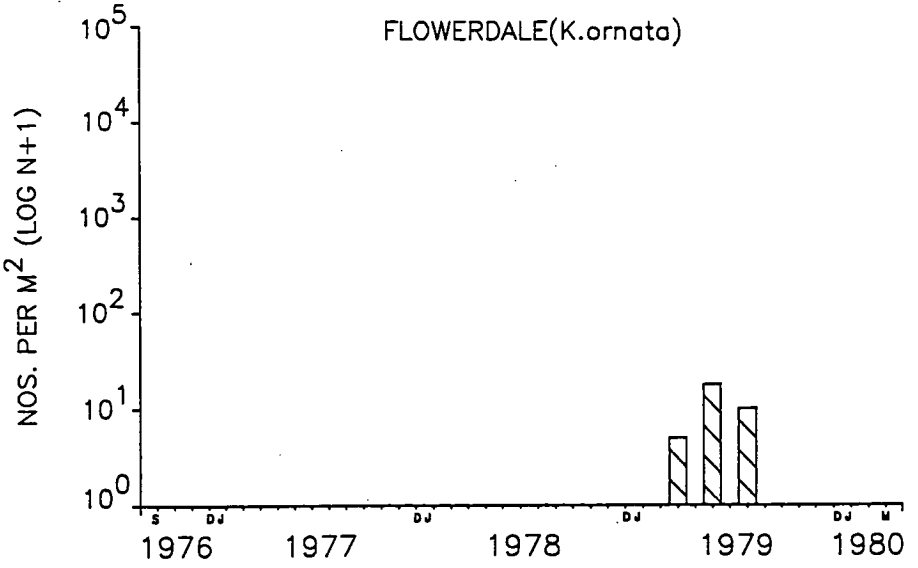
60


FLOWERDALE(K.oceanica var. schoetti)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
M
1976
1977
1978
1979
1980

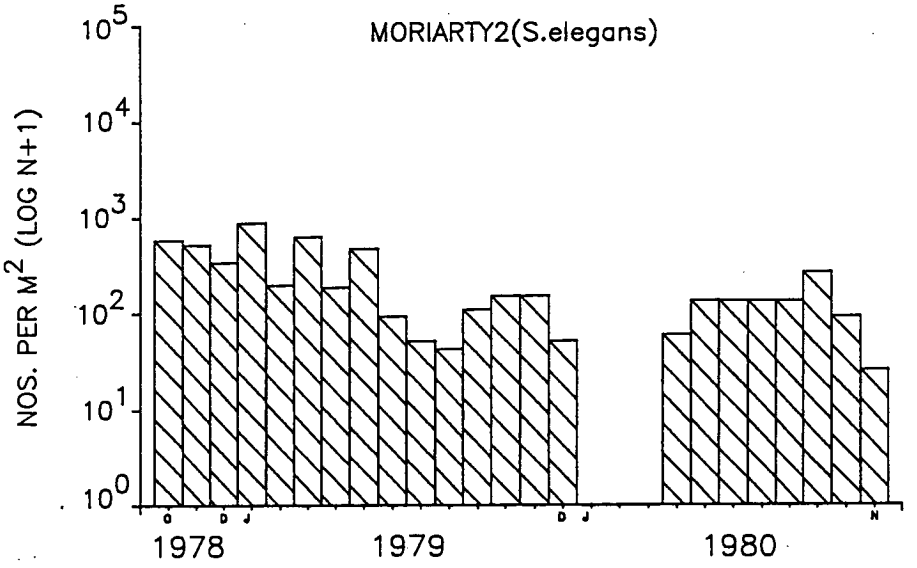
61


MORIARTY2(K.ornata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D
J
D
J
N
1978
1979
1980

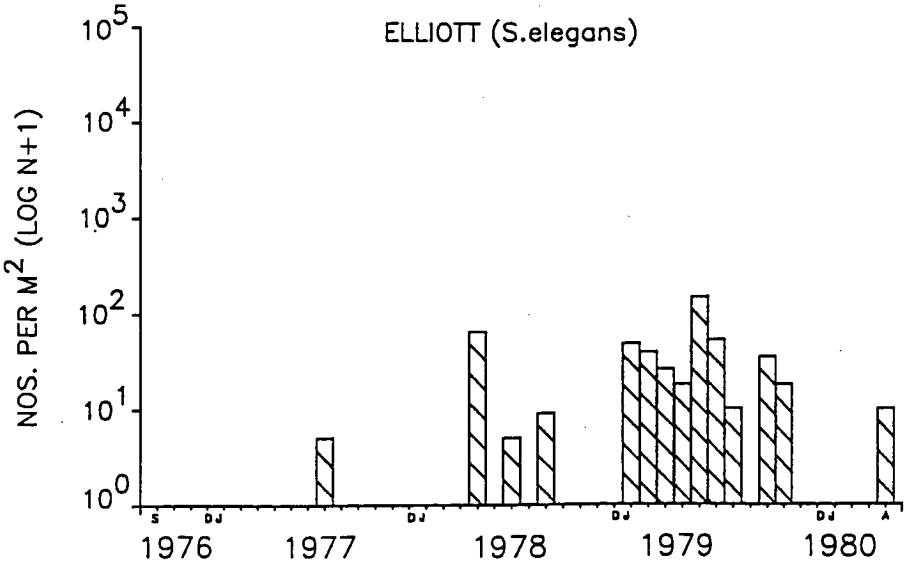
62


FLOWERDALE(K.ornata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

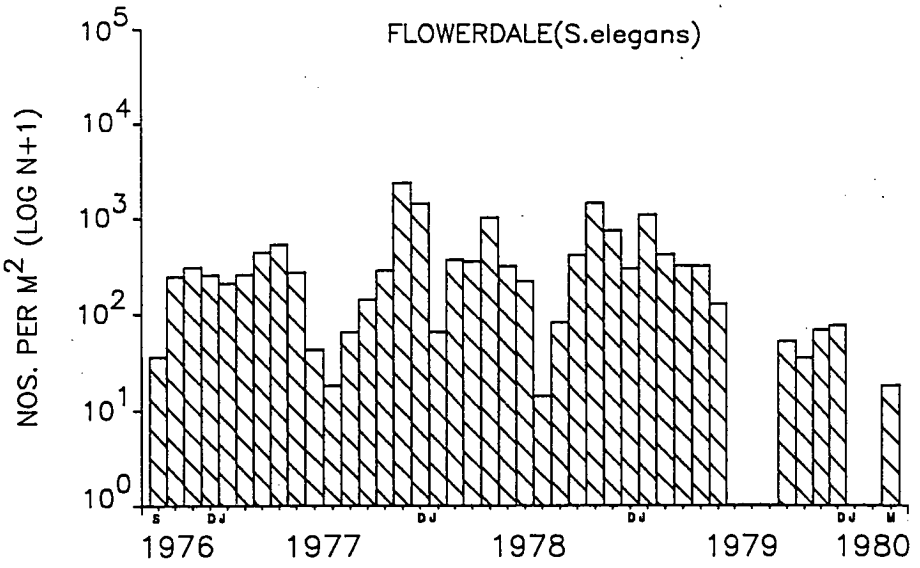
63


MORIARTY2(S.elegans)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1978
1979
1980

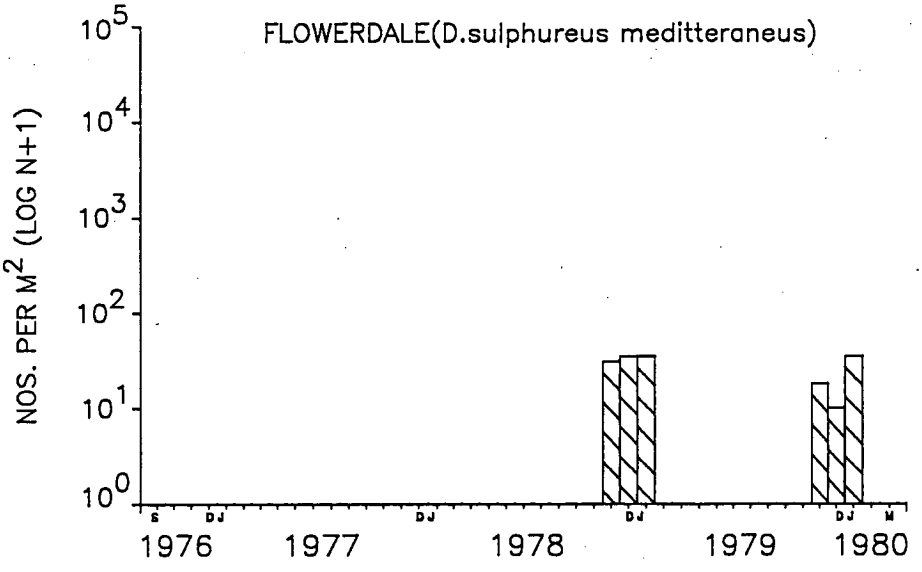
64


ELLIOTT (S.elegans)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

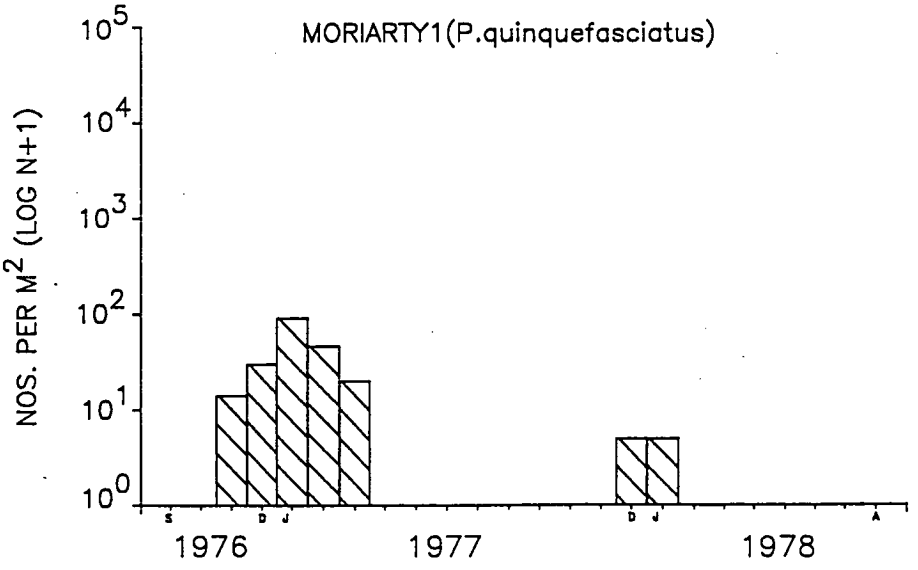
65


FLOWERDALE(S.elegans)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
M
1976
1977
1978
1979
1980

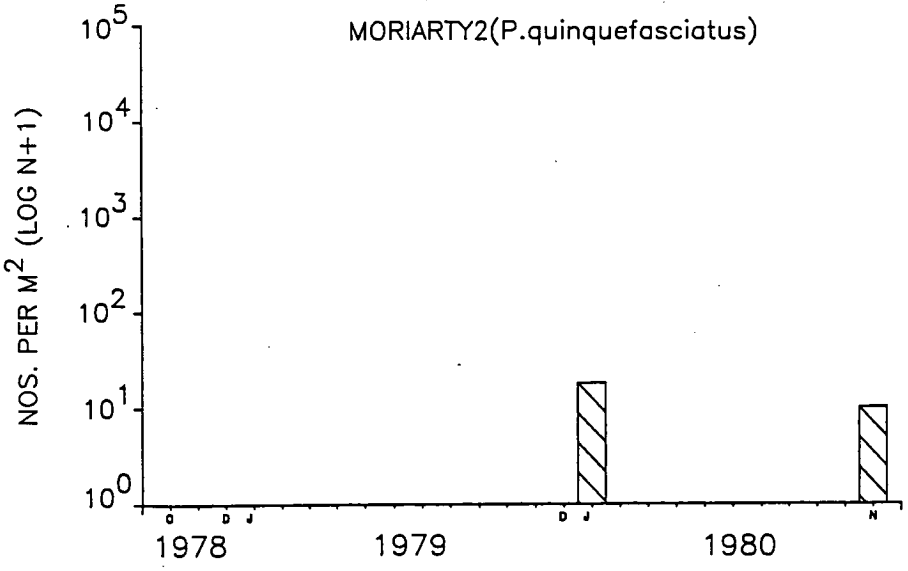
66


FLOWERDALE(D.sulphureus meditteraneus)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
M
1976
1977
1978
1979
1980

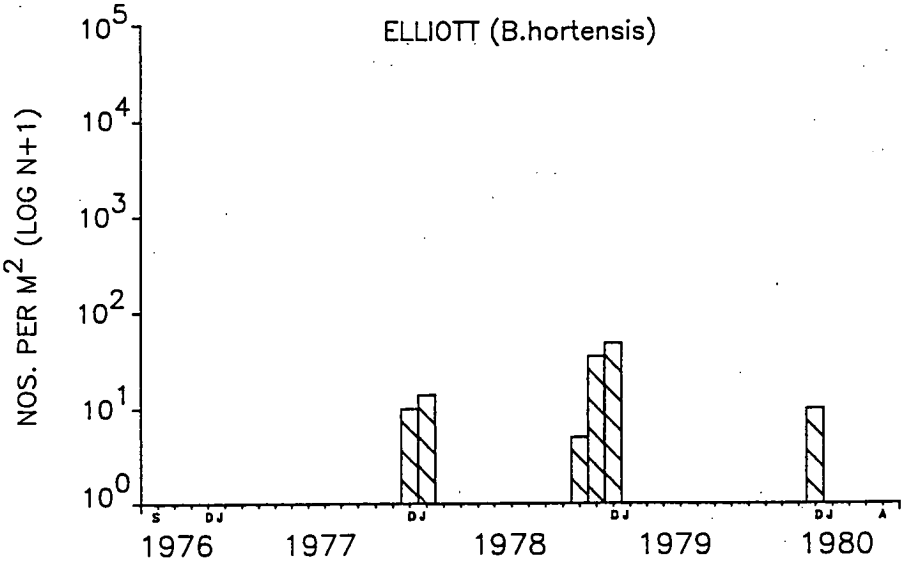
67


MORIARTY1(P.quinquefasciatus)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D
J
D
J
A
1976
1977
1978

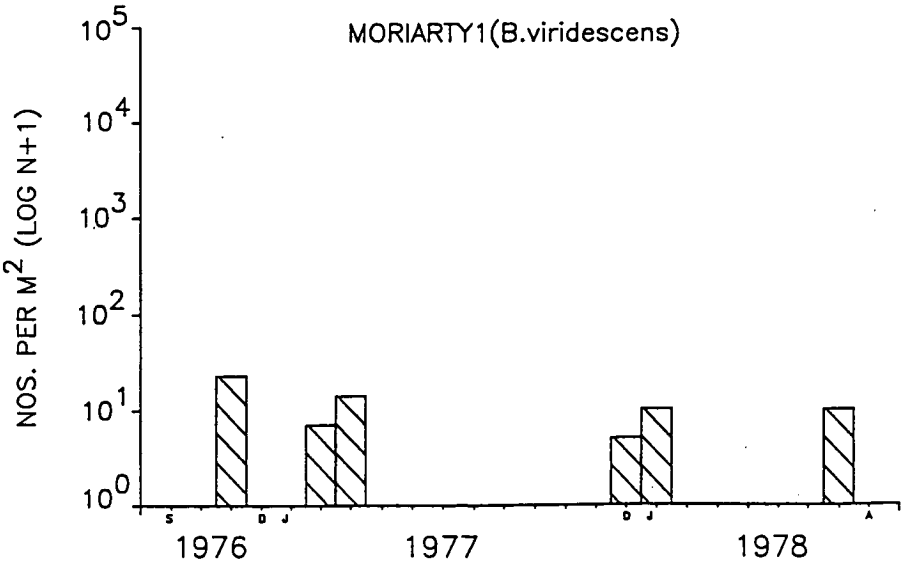
68


MORIARTY2(P.quinquefasciatus)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1978
1979
1980

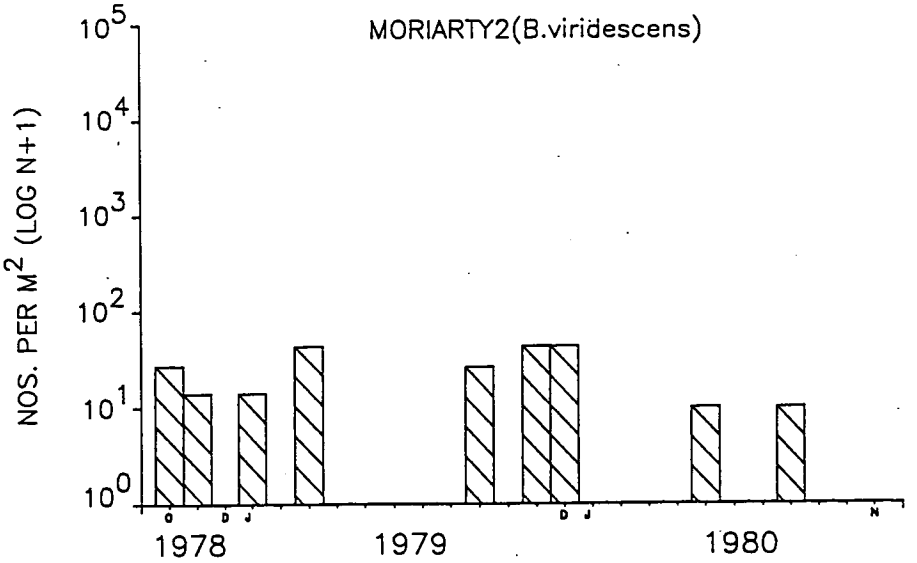
69


ELLIOTT (B.hortensis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

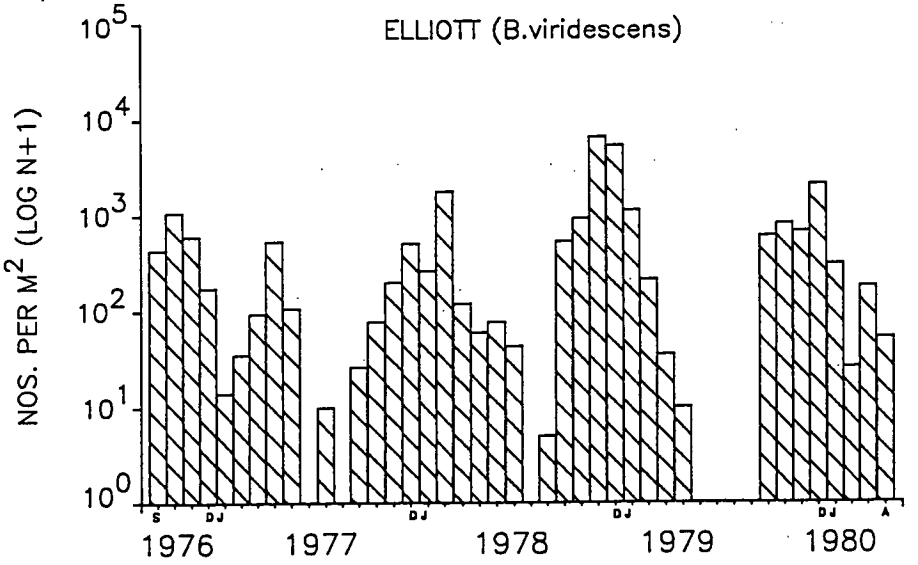
70


MORIARTY1(B.viridescens)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978

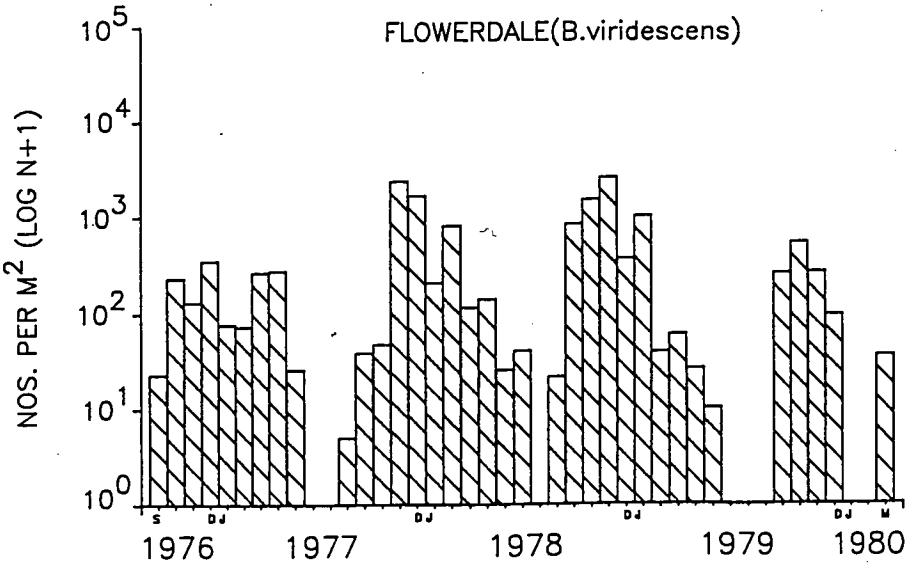
71


MORIARTY2(B.viridescens)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1978
1979
1980

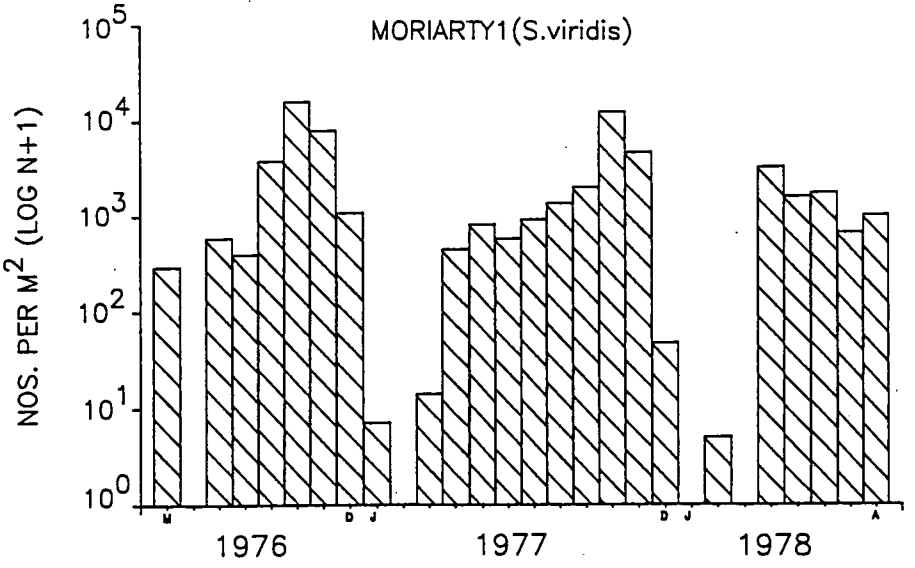
72


ELLIOTT (B.viridescens)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

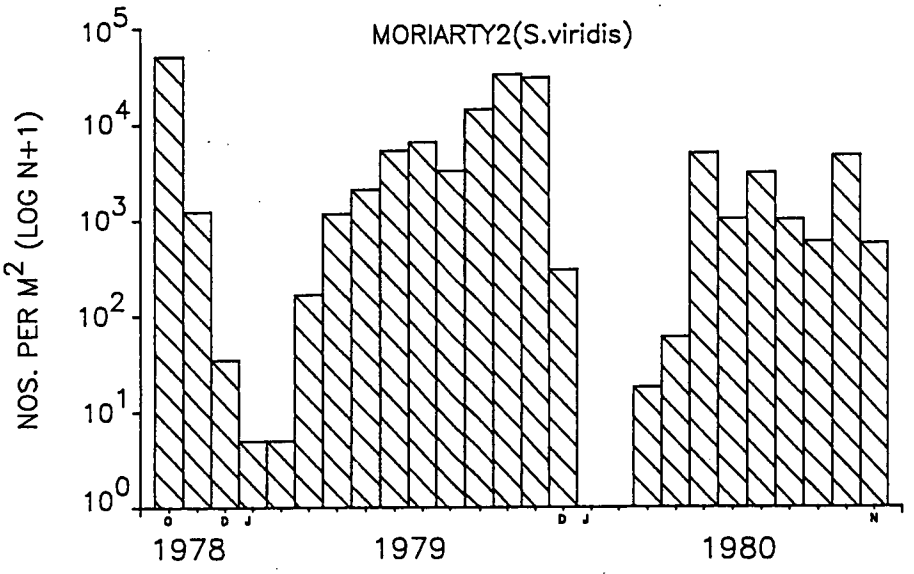
73


FLOWERDALE(B.viridescens)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

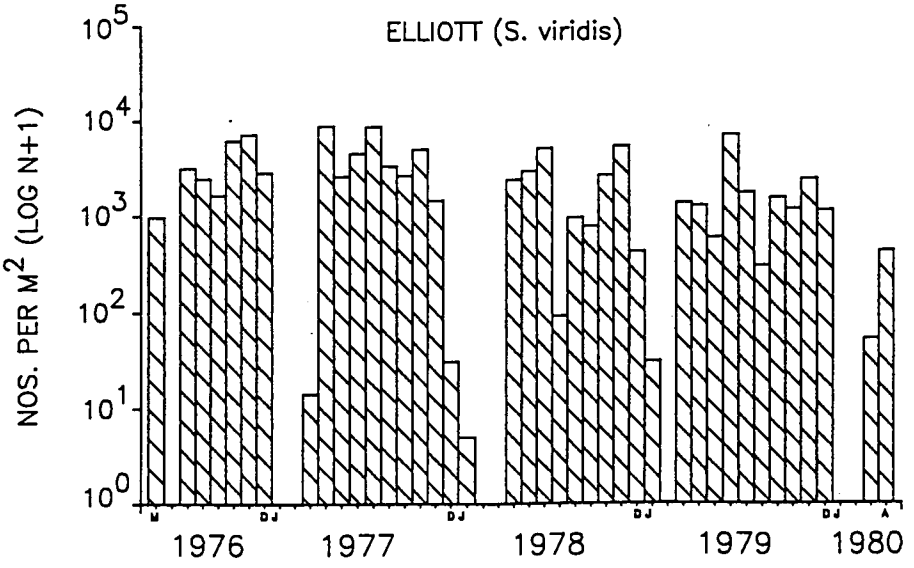
74


MORIARTY1(S.viridis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
D J
D J
A
1976
1977
1978

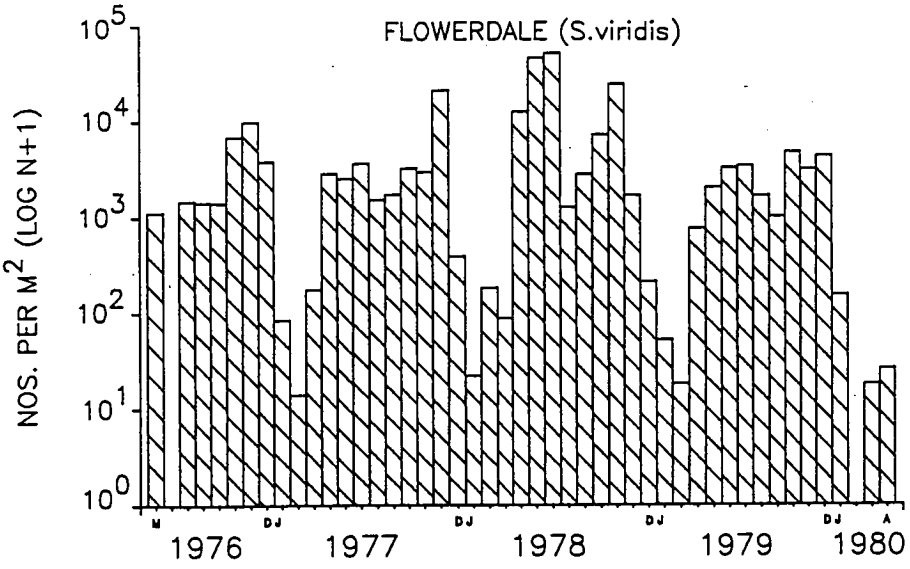
75


MORIARTY2(S.viridis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D J
D J
N
1978
1979
1980

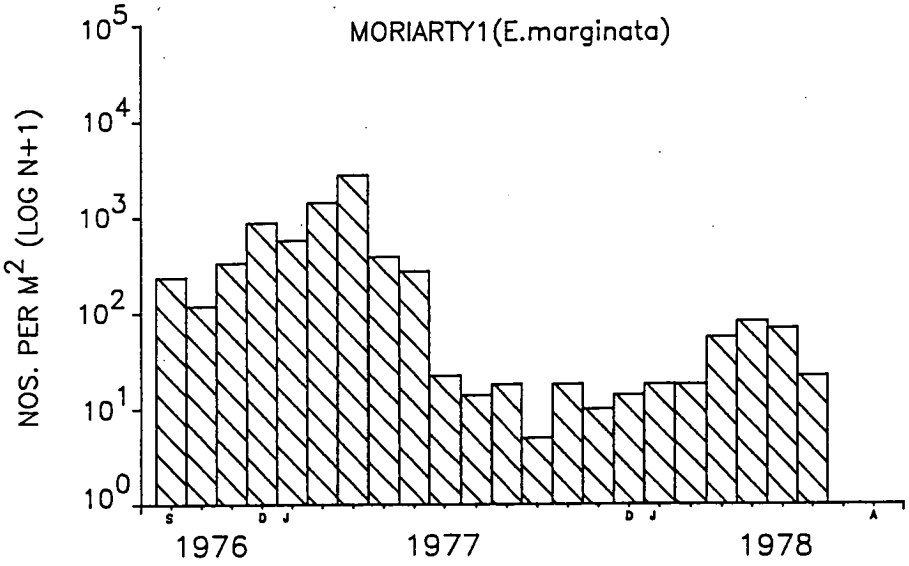
76


ELLIOTT (S. viridis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

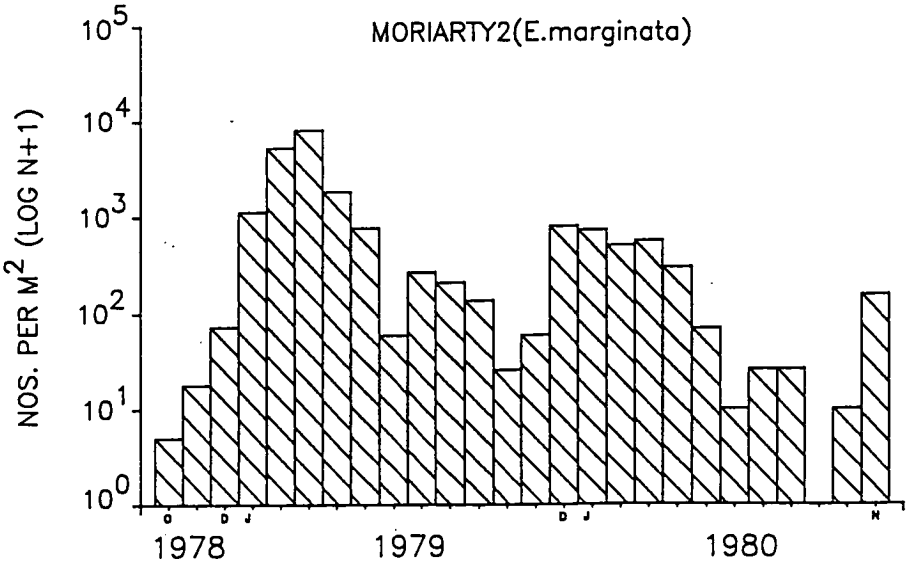
77


FLOWERDALE (S.viridis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
M
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

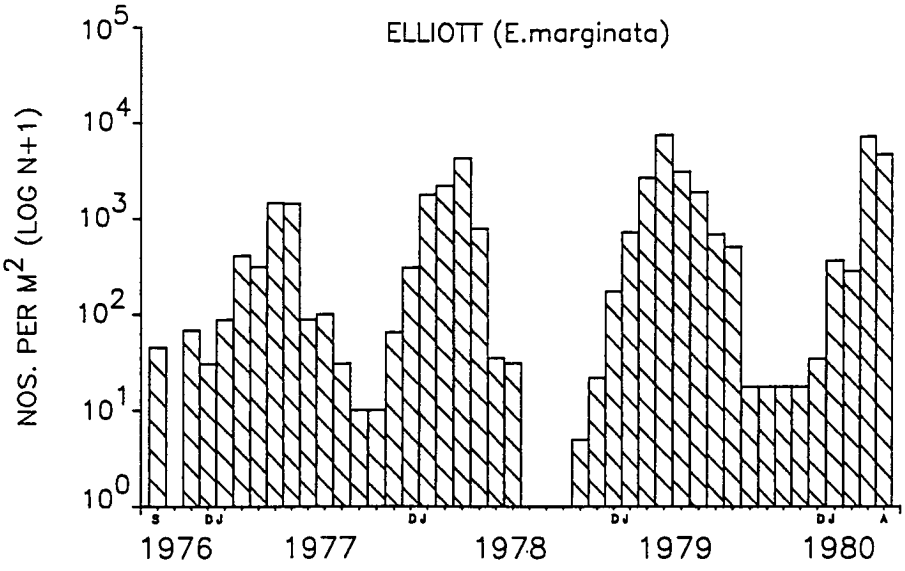
78


MORIARTY1 (E.marginata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D J
D J
A
1976
1977
1978

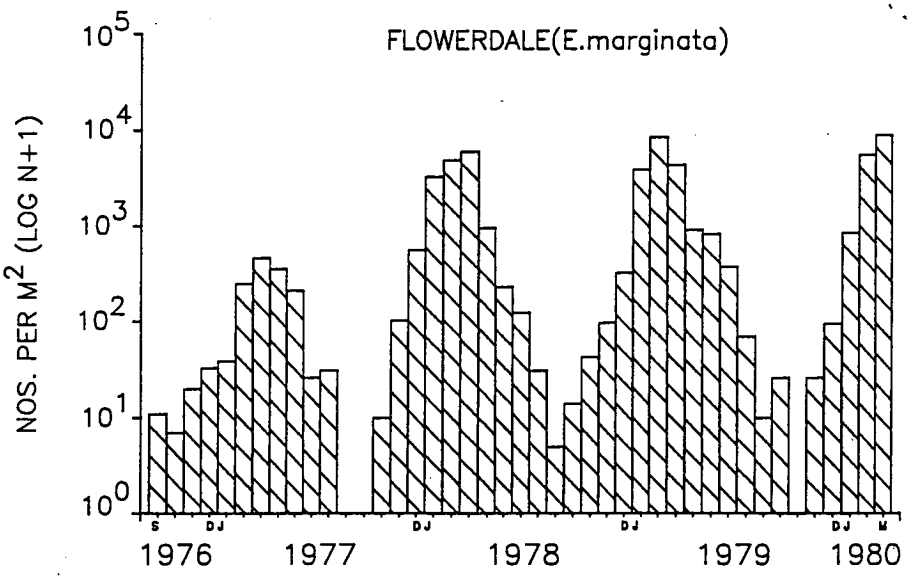
79


MORIARTY2(E.marginata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D J
D J
N
1978
1979
1980

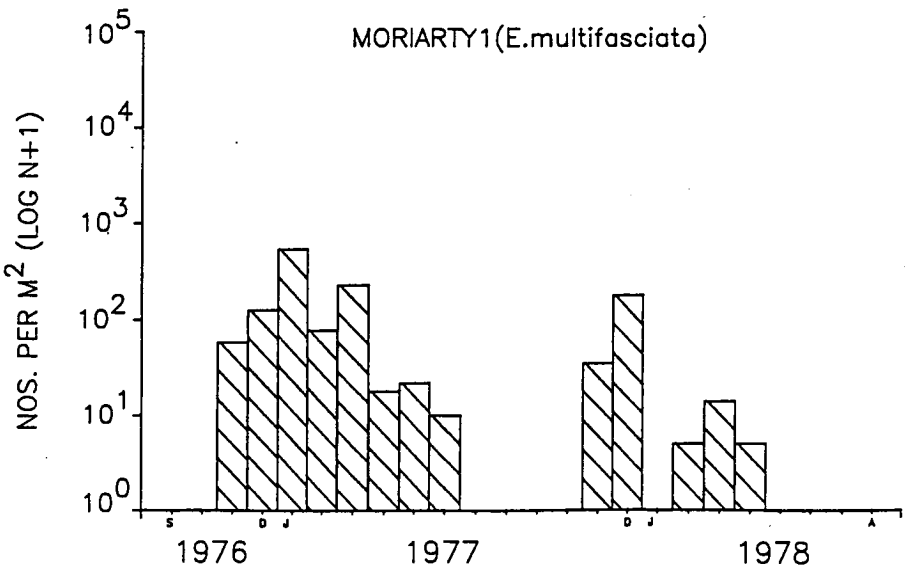
80


ELLIOTT (E.marginata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

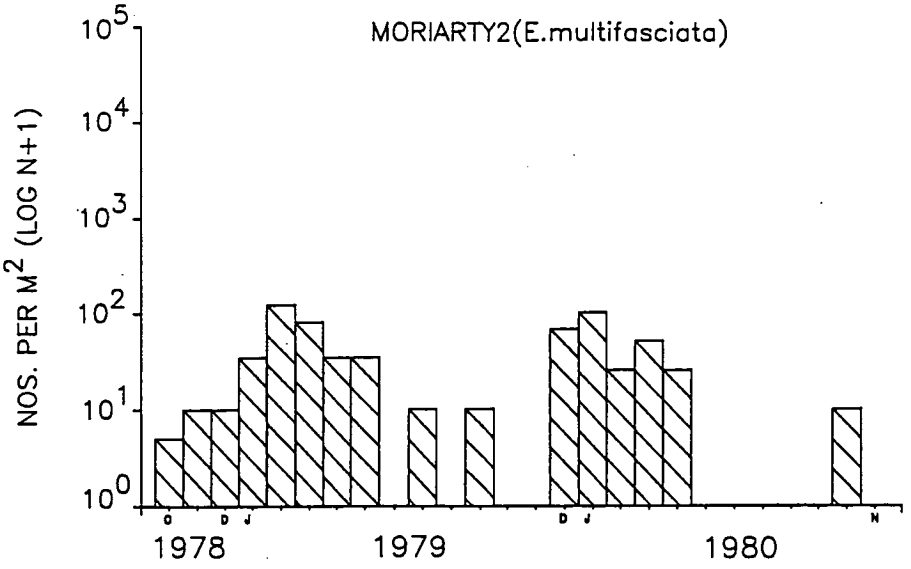
81


FLOWERDALE(E.marginata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
M
1976
1977
1978
1979
1980

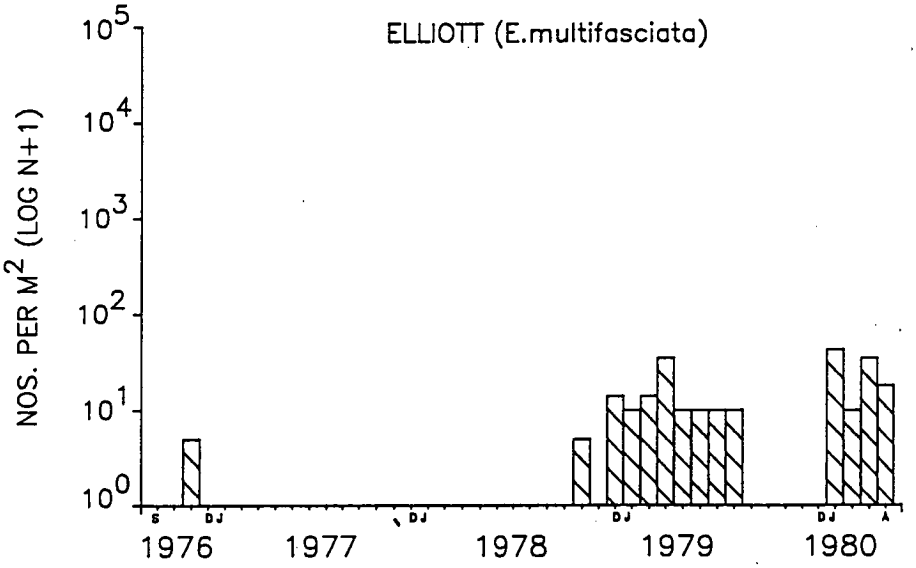
82


MORIARTY1(E.multifasciata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D J
D J
A
1976
1977
1978

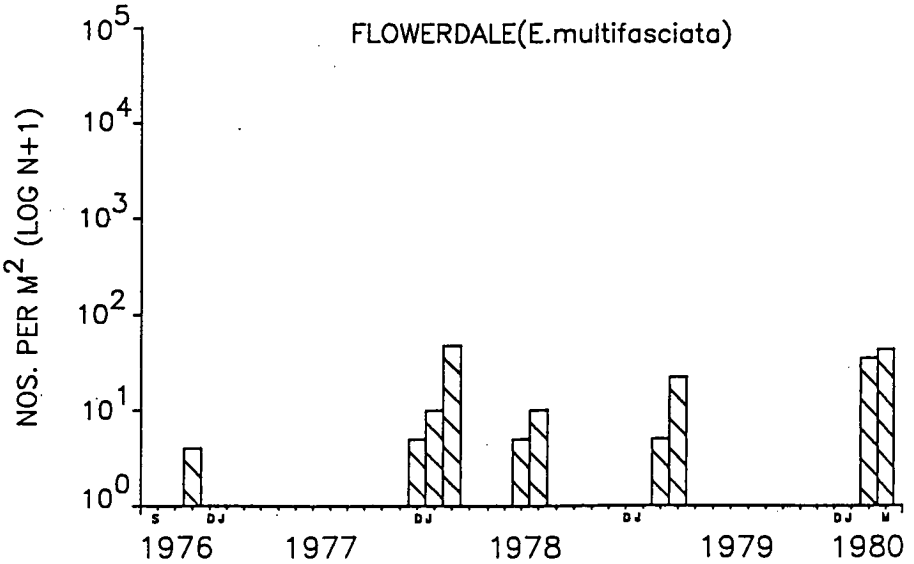
83


MORIARTY2(E.multifasciata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1978
1979
1980

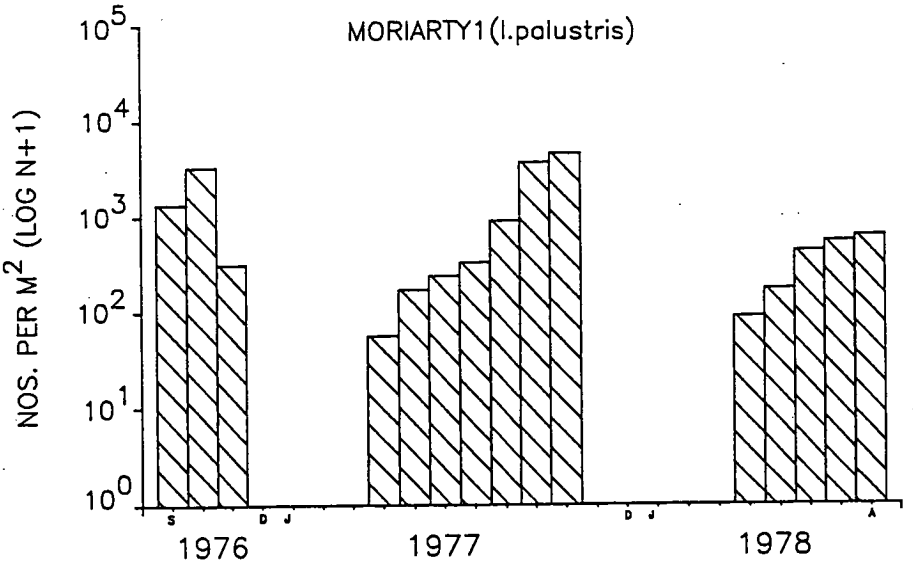
84


ELLIOTT (E.multifasciata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

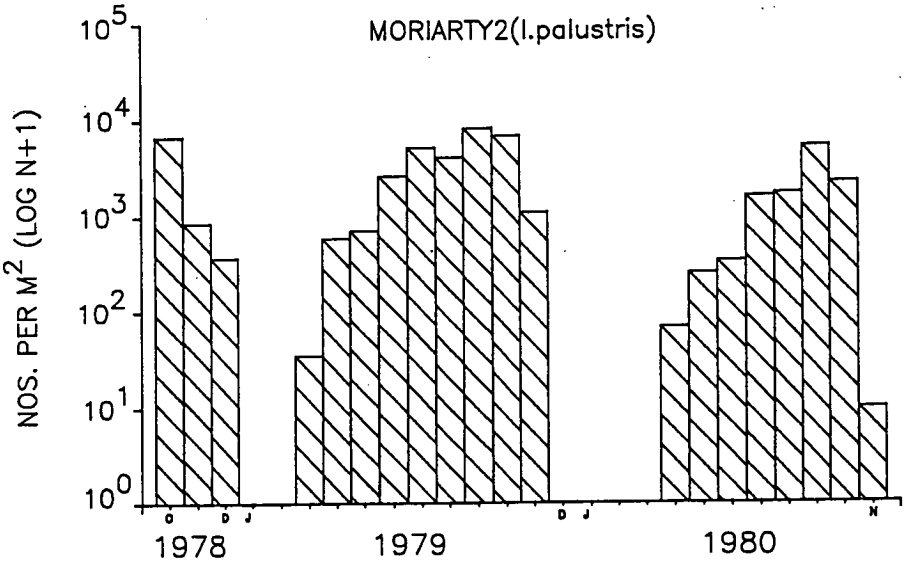
85


FLOWERDALE(E.multifasciata)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

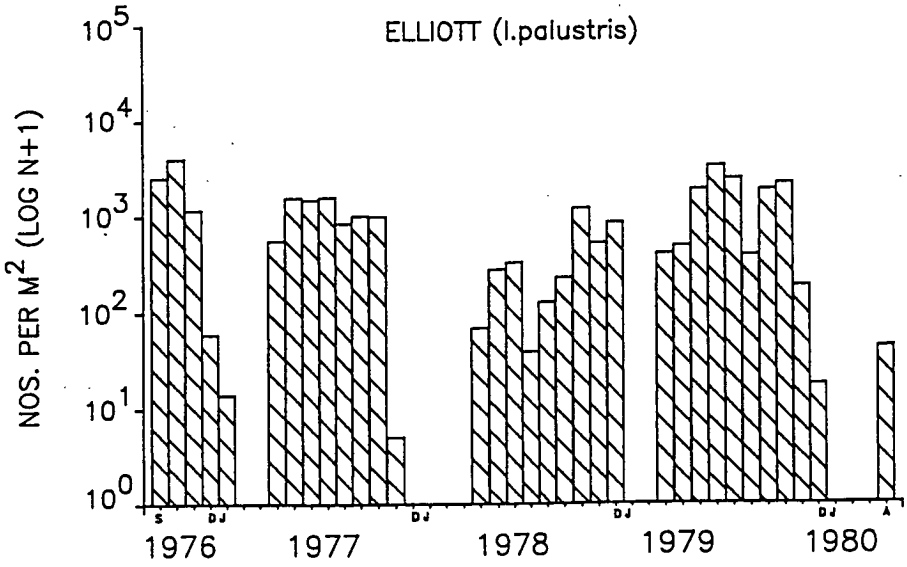
86


MORIARTY1 (I.palustris)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D J
D J
A
1976
1977
1978

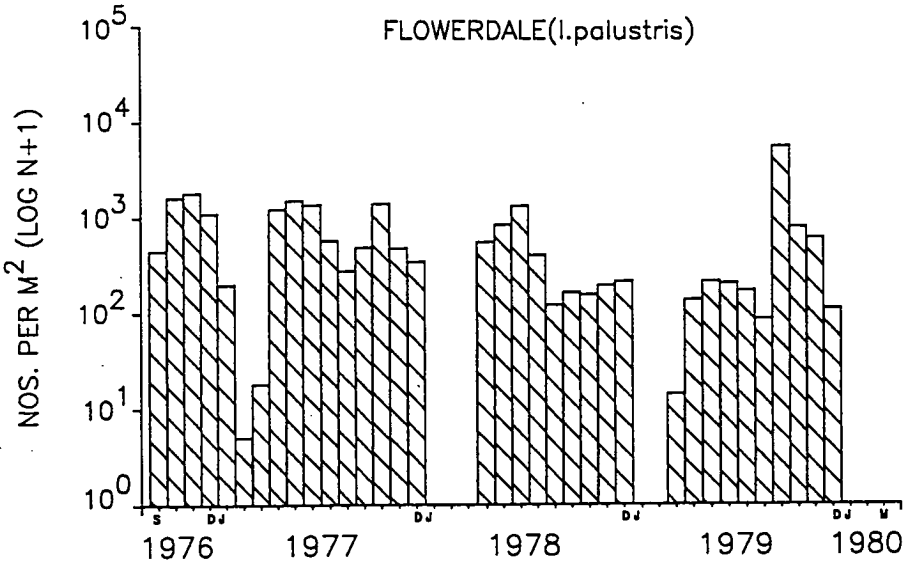
87


MORIARTY2(I.palustris)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D J
D J
N
1978
1979
1980

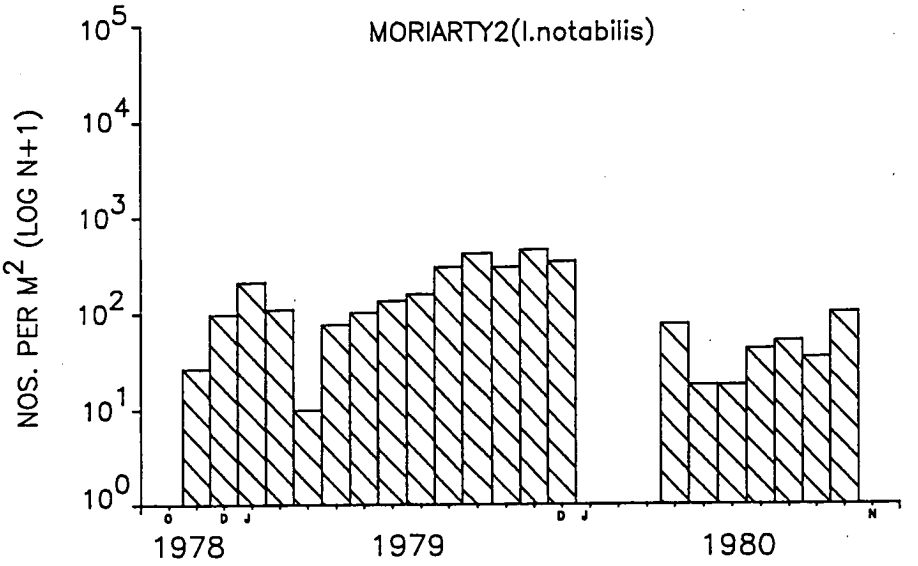
88


ELLIOTT (I.palustris)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

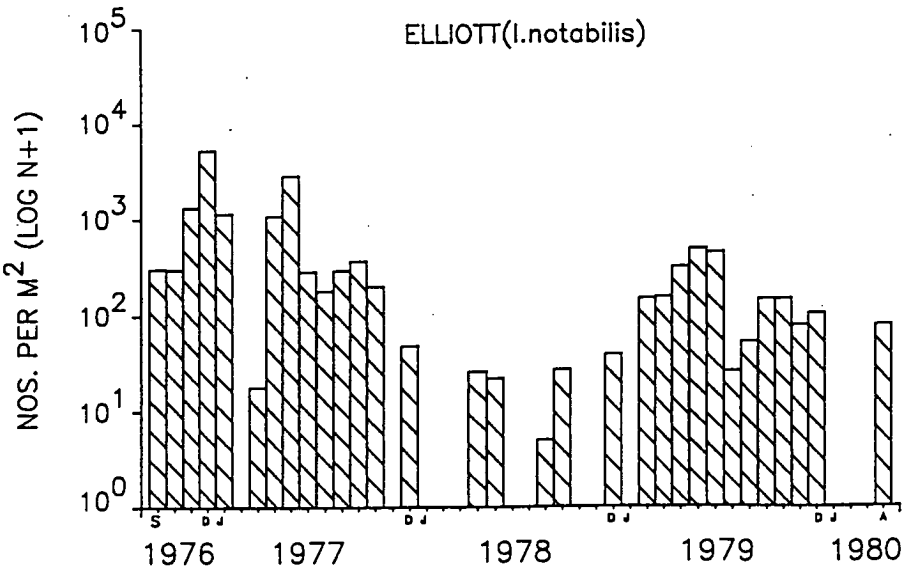
89


FLOWERDALE(I.palustris)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
M
1976
1977
1978
1979
1980

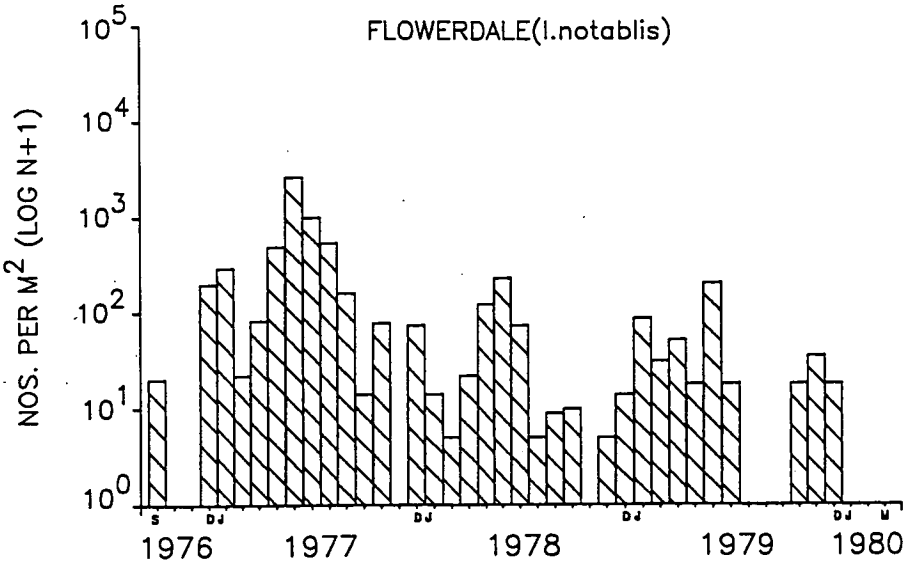
90


MORIARTY2(I.notabilis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D
J
D
J
N
1978
1979
1980

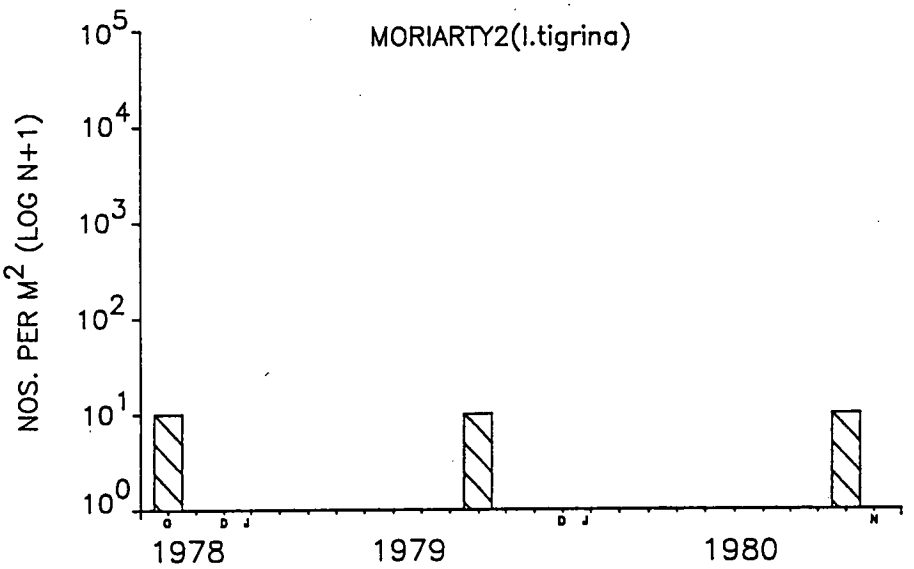
91


ELLIOTT(I.notabilis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
A
1976
1977
1978
1979
1980

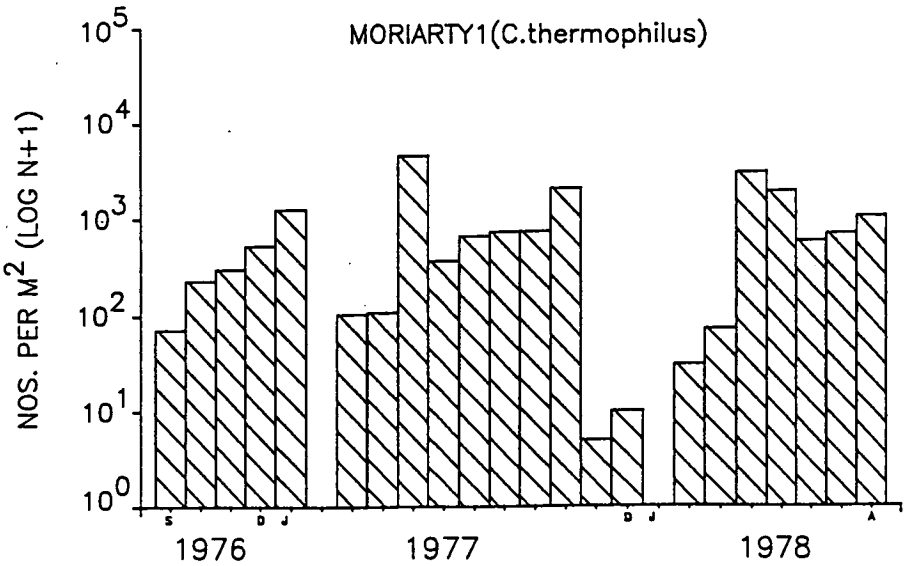
92


FLOWERDALE(I.notablis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
DJ
DJ
DJ
DJ
M
1976
1977
1978
1979
1980

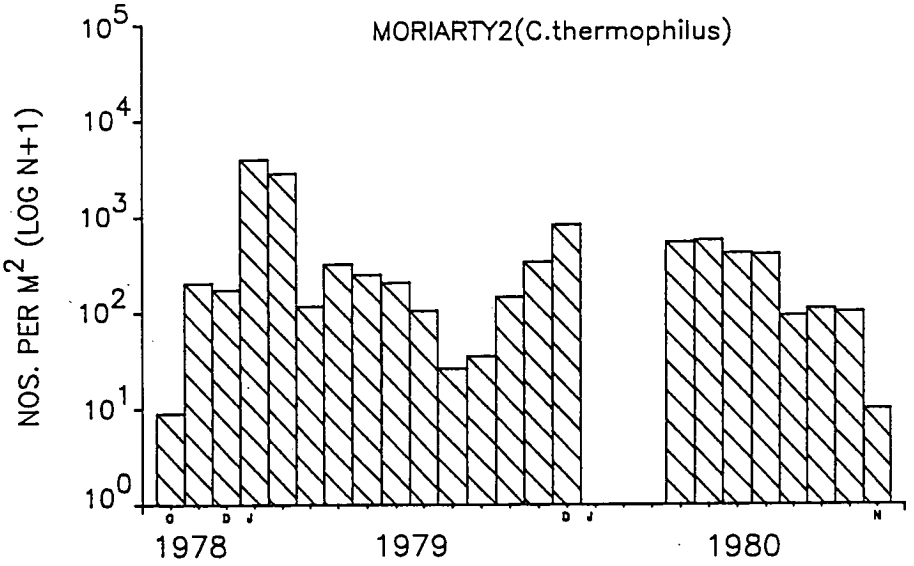
93


MORIARTY2(I.tigrina)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
O
D J
D J
N
1978
1979
1980

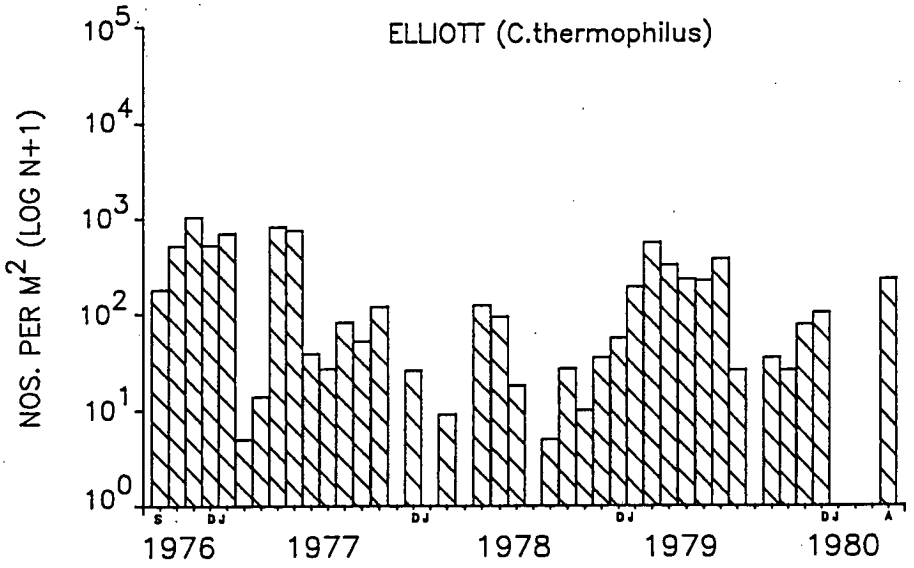
94


MORIARTY1(C.thermophilus)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D J
D J
A
1976
1977
1978

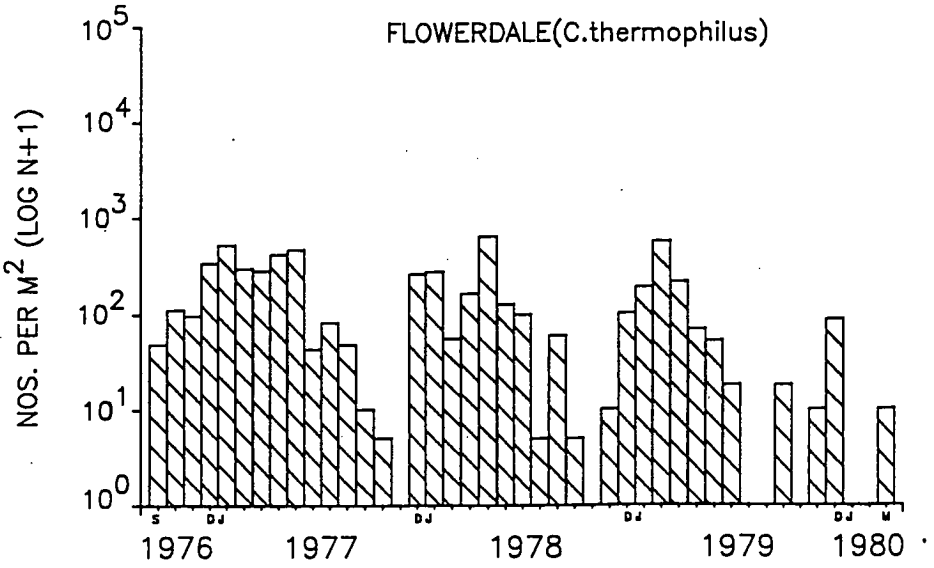
95


MORIARTY2(C.thermophilus)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1978
1979
1980

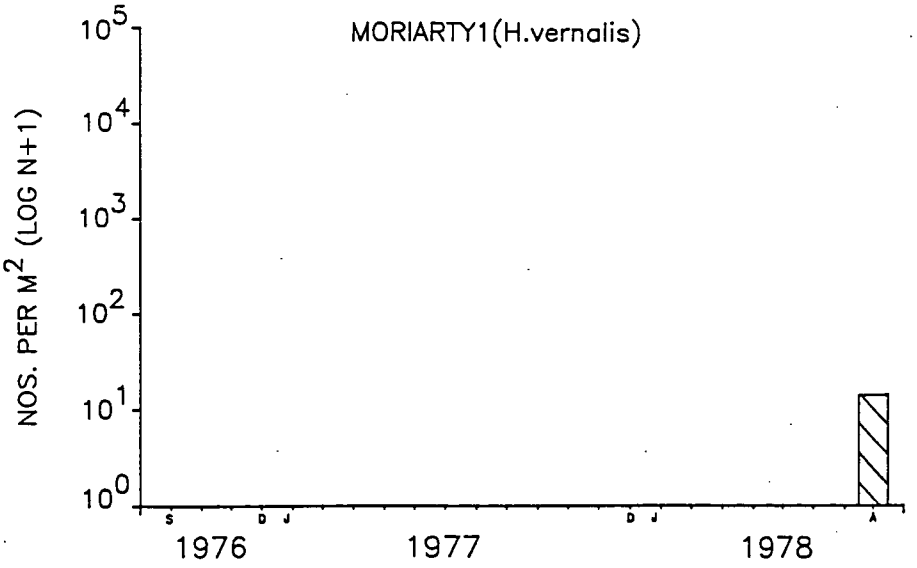
96


ELLIOTT (C.thermophilus)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

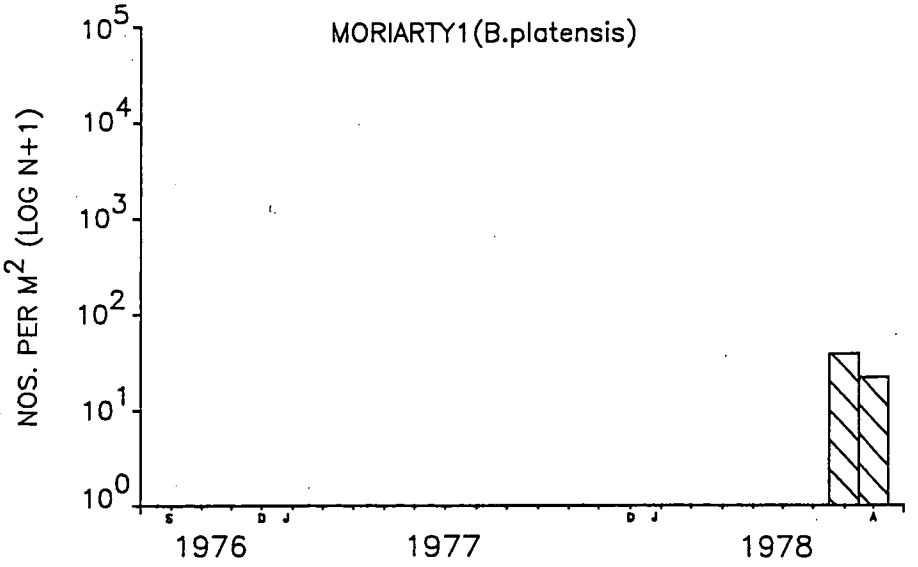
97


FLOWERDALE(C.thermophilus)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
1976
1977
1978
1979
1980

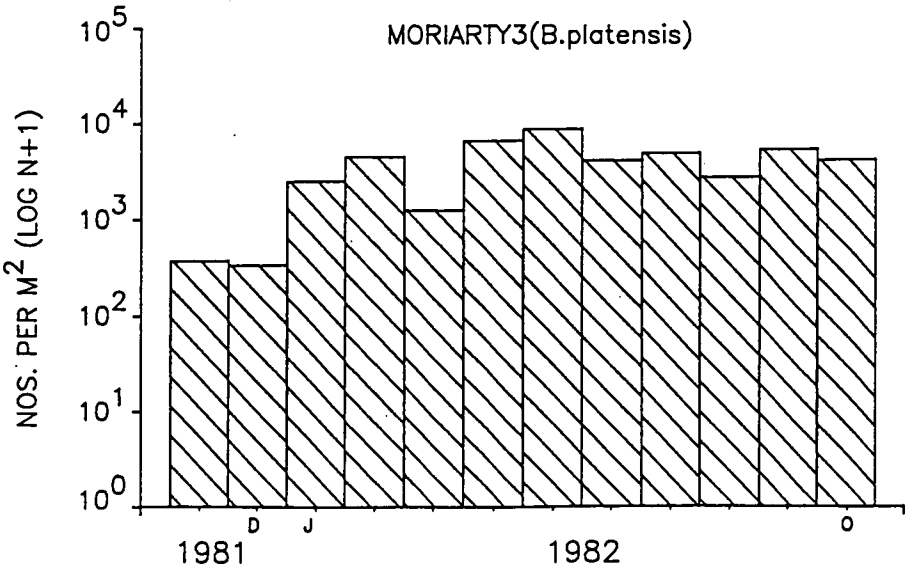
98


MORIARTY1(H.vernalis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D
J
D
J
A
1976
1977
1978

99


MORIARTY1(B.platensis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
S
D
J
D
J
A
1976
1977
1978

100


MORIARTY3(B.platensis)
NOS. PER M2 (LOG N+1)
10^5
10^4
10^3
10^2
10^1
10^0
D
J
O
1981
1982

101

KEY TO TABLE 8.5

* Site : M1 = Moriarty 1; M2 = Moriarty 2; M3 = Moriarty 3; E = Elliott; FL = Flowerdale

\+ Monthly sample periods : Moriarty 1: A = 13.9.76 - 28.8.78 (n = 24); B = 17.1.77 - 19.12.77 (n = 12).

Moriarty 2: A = 23.10.78 - 22.9.80 (n = 24); B = 23.10.78 - 24.9.79 (n = 12); C = 22.10.79 - 22.9.80) (n = 12); D = 22.1.79 - 18.12.79 (n = 12).

Moriarty 3: A = 26.11.81 - 26.10.82 (n = 12).

Elliott: A = 14.9.76 - 21.4.80 (n = 44); B = 17.1.77 - 20.12.77 (n = 12); C = 17.1.77 - 18.12.78 (n = 24); D = 23.1.78 - 18.12.78 (n = 12); E = 22.1.79 - 18.12.79 (n = 12); F = 23.1.78 - 18.12.79 (n = 24).

Flowerdale: A = 15.9.76 - 24.3.80 (n = 43); B = 18.1.77 - 19.12.77 (n = 12); C = 18.1.77 - 18.12.78 (n = 24); D = 24.1.78 - 18.12.78 (n =12); E = 22.1.79 - 18.12.79 (n = 12); F = 24.1.78 - 18.12.79 (n = 24).

++ Significance levels: 1 = $0.05 > P > 0.02$; 2 = $0.02 > P > 0.01$; 3 = $0.01 > P > 0.001$; 4 = $P < 0.001$.

+++ Signs indicate positive or negative regression; figures in brackets are coefficients of determination.

Table 8.5 Correlation levels of rainfall (R) (mm) and mean temperature (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date.									
			0-14 days		14-28 days (14 day lag)		28 days		14-42 days (14 day lag)		28-56 days (28 day lag)	
			R	T	R	T	R	T	R	T	R	T
cf. Dicyrtomina sp.	FL	A	+1 (10.8)	-4 (42.3)	ns	-4 (35.9)	+2 (16.6)	-4 (35.7)	+2 (16.2)	-4 (34.0)	+2 (15.2)	-4 (28.0)
		B	ns	-2 (46.8)	ns	-2 (49.0)	ns	-2 (49.2)	ns	-3 (63.7)	ns	-4 (75.3)
		C	ns	-3 (33.3)	ns	-3 (33.5)	ns	-3 (35.8)	ns	-3 (36.7)	ns	-3 (35.0)
		D	ns	-1 (38.8)	ns	ns	+1 (34.4)	-1 (39.3)	ns	ns	ns	ns
		E	ns	-3 (59.2)	ns	-3 (57.1)	ns	-3 (55.7)	ns	-2 (47.6)	ns	ns
		F	ns	-3 (44.2)	ns	-3 (39.0)	+1 (20.3)	-3 (41.5)	+2 (25.2)	-3 (33.6)	ns	-2 (24.5)
S. pumilis	M1	A	ns	-3 (30.1)	ns	-2 (24.6)	ns	-3 (31.7)	ns	-3 (29.0)	ns	-2 (25.8)
		B	ns	-2 (43.5)	ns	-2 (45.4)	ns	-3 (52.4)	ns	-3 (58.4)	ns	-3 (53.0)
	M2	A	+1 (21.6)	-3 37.8	+2 (27.6)	-3 (35.2)	+3 (39.2)	-4 (28.9)	+3 (33.4)	-4 (45.9)	+2 (24.7)	-4 (51.6)
		B	ns	ns	ns	ns	ns	ns	ns	-1 (37.7)	ns	-3 (50.7)
		C	+1 (43.1)	-3 (62.2)	+1 (40.8)	-3 (63.0)	+3 (51.7)	-3 (65.0)	+3 (51.3)	-4 (69.0)	+1 (39.8)	-4 (72.6)
		D	ns	ns	+1 (33.3)	-1 (34.1)	+1 (42.9)	-1 35.5)	ns	-2 (47.5)	ns	-3 (57.8)
	E	A,C,D, E,F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		B	ns	ns	ns	-1 (33.8)	ns	ns	ns	ns	ns	ns
	FL	A,B,C, D,E	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		F	ns	+2 (49.1)	ns	+3 (52.6)	ns	+3 (52.6)	ns	+2 (48.4)	ns	+1 (37.9)

Table 8.5 (cont.) Correlation levels of rainfall (R) (mm) and mean temperature (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date.									
			0-14 days		14-28 days (14 day lag)		28 days		14-42 days (14 day lag)		28-56 days (28 day lag)	
			R	T	R	T	R	T	R	T	R	T
K. australis	E	A	ns	-4 (33.1)	ns	-4 (30.0)	+2 (30.0)	-4 (30.6)	ns	-2 (15.2)	+3 (19.5)	-3 (21.7)
		B	ns	-2 (47.3)	ns	-1 (38.7)	ns	-2 (44.1)	ns	ns	ns	ns
		C	ns	-3 (32.8)	ns	-2 (26.3)	ns	-2 (27.9)	ns	ns	+1 (19.1)	ns
		D	ns	ns	ns	ns	ns	ns	ns	ns	+1 (42.0)	ns
		E	ns	-1 (37.1)	ns	ns	ns	ns	ns	ns	ns	ns
		F	ns	-3 (31.8)	ns	-2 (24.3)	ns	-2 (25.6)	ns	ns	ns	ns
	FL	A,B,C, D,E,F,	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
K. oceanica var. schoetti	FL	A	ns	ns	ns	+1 (13.0)	ns	+1 (13.1)	ns	+1 (12.3)	ns	+1 (14.5)
		B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		C	ns	+2 (25.8)	ns	+3 (38.1)	ns	+3 (32.5)	ns	+3 (35.0)	ns	+3 (30.2)
		D	ns	+3 (59.7)	ns	+4 (69.0)	ns	+3 (65.9)	ns	+4 (72.5)	ns	+4 (71.1)
		E	ns	+1 (37.5)	ns	+2 (47.4)	ns	+2 (46.4)	ns	+3 (52.6)	ns	+3 (60.0)
		F	-2 (28.1)	+3 (37.7)	ns	+3 (42.5)	-3 (29.7)	+3 (41.8)	ns	+4 (45.0)	ns	+4 (50.0)
K. ornata	M2	A	ns	-3 (37.0)	ns	-3 (40.1)	ns	-3 (40.6)	ns	-3 (31.5)	ns	ns
		B	ns	-3 (65.1)	ns	-3 (52.1)	ns	-3 (61.4)	ns	-1 (42.4)	ns	ns
		C	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		D	ns	-3 (64.1)	ns	-3 (52.2)	ns	-3 (59.8)	ns	-1 (39.2)	ns	ns

Table 8.5 (cont.) Correlation levels of rainfall (R) (mm) and mean temperature (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date. 0-14 days R	0-14 days T	14-28 days (14 day lag) R	14-28 days (14 day lag) T	28 days R	28 days T	14-42 days (14 day lag) R	14-42 days (14 day lag) T	28-56 days (28 day lag) R	28-56 days (28 day lag) T
S. elegans	M2	A	+1 (22.2)	ns	ns	ns	ns	ns	ns	ns	+1 (23.8)	ns
		B	ns	+2 (46.4)	ns	+2 (44.6)	ns	+2 (48.0)	ns	+1 (48.0)	ns	ns
		C	+2 (47.4)	-3 (52.6)	ns	-3 (63.6)	+2 (46.2)	-3 (59.7)	+1 (36.5)	-4 (67.8)	+1 (41.4)	-3 (57.8)
		D	ns	+1 (35.5)	ns	+1 (35.7)	ns	+1 (38.5)	ns	+1 (38.5)	ns	+1 (37.5)
	FL	A,D	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		B	ns	ns	ns	+3 (55.7)	ns	+2 (46.1)	ns	+3 (55.7)	ns	ns
		C	ns	+1 (20.8)	ns	+3 (32.0)	ns	+2 (25.9)	ns	+2 (24.5)	ns	ns
		E	ns	+3 (60.9)	ns	+3 (57.5)	ns	+3 (63.4)	ns	+3 (66.0)	ns	+3 (55.3)
		F	ns	+3 (29.1)	ns	+3 (31.6)	ns	+3 (31.2)	ns	+3 (32.1)	ns	+3 (25.8)
P. quinquefasciatus	M1	A	ns	+3 (36.4)	ns	+1 (20.4)	ns	+3 (33.5)	ns	+1 (23.4)	ns	ns
		B	ns	+4 (71.0)	ns	+1 (40.5)	ns	+3 (63.6)	ns	+2 (49.8)	ns	+1 (39.6)
B. viridescens	E	A	ns	+3 (21.4)	ns	+4 (16.9)	ns	+4 (21.3)	ns	ns	ns	+1 (11.3)
		B	ns	ns	ns	+1 (34.4)	ns	ns	-1 (38.2)	ns	ns	ns
		C	-1 (21.0)	+2 (25.9)	ns	+2 (27.4)	-1 (21.6)	+3 (30.7)	ns	ns	ns	+2 (24.8)
		D	ns	+1 (36.4)	ns	ns	-1 (42.7)	+1 (41.6)	ns	ns	ns	ns
		E	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		F	ns	+3 (32.7)	ns	+1 (23.6)	ns	+3 (31.0)	ns	ns	ns	ns

Table 8.5 (cont.) Correlation levels of rainfall (R) (mm) and mean temperature (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date.									
			0–14 days		14–28 days (14 day lag)		28 days		14–42 days (14 day lag)		28–56 days (28 day lag)	
			R	T	R	T	R	T	R	T	R	T
B. viridescens	FL	A	ns	+3 (17.8)	ns	+3 (17.6)	ns	+3 (19.1)	ns	+1 (11.1)	ns	ns
		B	−1 (37.9)	+1 (40.2)	ns	+3 (52.0)	ns	+3 (47.4)	ns	+3 (38.8)	ns	ns
		C	−3 (34.6)	+3 (34.2)	ns	+3 (41.4)	ns	+3 (38.2)	ns	+3 (29.3)	ns	ns
		D	ns	ns	ns	ns	−1 (37.0)	ns	ns	ns	ns	ns
		E	+1 (37.7)	+1 (35.4)	ns	ns	ns	ns	ns	ns	ns	ns
		F	ns	+3 (29.9)	ns	+2 (24.4)	ns	+2 (26.5)	ns	ns	ns	ns
S. viridis	M1	A	ns	−4 (51.1)	ns	−4 (45.2)	ns	−4 (53.1)	ns	−4 (49.5)	ns	−4 (45.3)
		B	ns	−3 (58.3)	ns	−2 (43.8)	ns	−3 (58.4)	ns	−3 (56.0)	ns	−3 (50.9)
	M2	A	ns	−4 (54.3)	ns	−4 (57.0)	+1 (19.6)	−4 (57.5)	+1 (23.2)	−4 (56.4)	ns	−4 (50.3)
		B	ns	−4 (71.1)	ns	−4 (72.7)	ns	−4 (73.8)	ns	−3 (65.9)	ns	−3 (51.6)
		C	+2 (48.3)	−2 (43.9)	+1 (41.7)	−2 (47.2)	+3 (55.3)	−2 (47.2)	+3 (58.0)	−3 (52.2)	+3 (59.8)	−3 (53.4)
		D	ns	−3 (61.1)	ns	−3 (61.9)	ns	−3 (62.9)	ns	−3 (62.9)	ns	−3 (55.6)
	E	A	ns	−4 (48.4)	ns	−4 (47.3)	+2 (44.3)	−4 (46.7)	ns	−4 (30.6)	+3 (32.8)	−4 (37.8)
		B	ns	−4 (78.7)	ns	−3 (58.4)	ns	−4 (70.3)	ns	−1 (38.3)	ns	−2 (49.5)
		C	ns	−4 (55.9)	ns	−4 (48.5)	ns	−4 (50.0)	ns	−3 (30.3)	+3 (26.8)	−3 (36.3)
		D	ns	−1 (36.7)	ns	−1 (36.9)	ns	ns	ns	ns	+1 (36.3)	ns

Table 8.5 Correlation levels of rainfall (R) (mm) and mean temperature (cont.) (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date.									
			0-14 days		14-28 days (14 day lag)		28 days		14-42 days (14 day lag)		28-56 days (28 day lag)	
			R	T	R	T	R	T	R	T	R	T
S. viridis		E	ns	-1 (34.5)	ns	-1 (42.3)	ns	-1 (36.9)	ns	ns	ns	-1 (34.9)
		F	ns	-3 (35.4)	ns	-3 (35.3)	ns	-3 (32.2)	ns	-1 (20.1)	+2 (24.9)	-2 (26.2)
	FL	A	ns	-4 (47.8)	+2 (15.4)	-4 (43.1)	+3 (23.9)	-4 45.2)	+3 (19.6)	-4 (38.7)	+1 (14.0)	-4 (27.4)
		B	ns	-3 (55.9)	ns	-1 (40.8)	ns	-2 (49.8)	ns	-1 (42.2)	ns	-1 (35.6)
		C	ns	-4 (45.2)	ns	-3 (33.2)	+1 (18.0)	-3 (42.2)	ns	-3 (30.5)	ns	-1 (21.2)
		D	ns	-1 (43.0)	ns	ns	ns	-1 (40.8)	+1 (33.9)	ns	+1 (42.7)	ns
		E	ns	-3 (53.4)	ns	-3 (58.4)	ns	-3 (54.3)	ns	-2 (49.7)	ns	-1 (33.7)
		F	ns	-4 (44.2)	+1 (19.3)	-3 (39.8)	ns	-4 (44.2)	+1 (19.3)	-3 (34.2)	ns	-1 (21.5)
E. marginata	M1	A	ns	+3 (35.6)	ns	+1 (22.2)	ns	+3 (34.9)	ns	+3 (31.6)	ns	+2 (26.2)
		B	ns	+3 (58.3)	ns	+1 (38.1)	ns	+3 (58.5)	ns	+3 (63.5)	ns	+4 (70.5)
	M2	A	ns	+3 (29.6)	ns	+3 (32.6)	ns	+3 (34.3)	ns	+4 (46.3)	ns	+4 (51.7)
		B	ns	ns	ns	ns	ns	ns	ns	+1 (39.2)	ns	+3 (56.2)
		C	-1 (37.1)	+3 (62.6)	-2 (45.8)	+4 (73.5)	-3 (51.4)	+4 (69.5)	ns	+4 (70.7)	ns	+3 (55.8)
		D	ns	+1 (35.3)	ns	+2 (46.0)	ns	+2 (44.8)	ns	+3 (65.8)	ns	+4 (79.8)
	E	A	-2 (12.7)	+4 (30.6)	ns	+4 (38.0)	-1 (9.8)	+4 (38.1)	-3 (21.9)	+4 (62.4)	ns	+4 (55.4)
		B	ns	ns	ns	ns	ns	ns	ns	ns	ns	+1 (42.8)

Table 8.5 (cont.) Correlation levels of rainfall (R) (mm) and mean temperature (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date.									
			0-14 days		14-28 days (14 day lag)		28 days		14-42 days (14 day lag)		28-56 days (28 day lag)	
			R	T	R	T	R	T	R	T	R	T
E. marginata	E	C	ns	+3 (42.3)	ns	+4 (47.6)	ns	+4 (49.7)	ns	+4 (67.2)	ns	+4 (63.2)
		D	ns	+4 (75.3)	ns	+4 (87.4)	ns	+4 (84.2)	-1 (39.8)	+4 (91.0)	ns	+4 (95.1)
		E	-3 (67.5)	ns	ns	ns	-1 (39.5)	ns	-3 (51.6)	+3 (64.2)	ns	+2 (45.2)
		F	-2 (25.0)	+3 (41.8)	ns	+4 (43.0)	-1 (18.9)	+4 (47.9)	-3 (32.4)	+4 (70.2)	ns	+4 (64.4)
	FL	A	-1 (11.4)	+4 (45.6)	ns	+4 (53.6)	-2 (15.1)	+4 (52.6)	-1 (13.0)	+4 (66.7)	-3 (18.5)	+4 (73.8)
		B	ns	+1 (35.4)	ns	+3 (55.7)	ns	+2 (46.1)	ns	+3 (55.7)	ns	+3 (62.0)
		C	ns	+4 (49.4)	ns	+4 (57.7)	ns	+4 (55.6)	ns	+4 (64.7)	ns	+4 (72.4)
		D	ns	+4 (68.6)	ns	+4 (73.8)	ns	+4 (75.5)	ns	+4 (85.4)	-1 (33.6)	+4 (91.9)
		E	-1 (33.2)	+1 (39.2)	-1 (38.4)	+2 (43.7)	-2 (47.0)	+2 (44.7)	-1 (36.4)	+3 (60.7)	ns	+4 (72.0)
		F	-1 (18.1)	+4 (51.4)	-1 (19.9)	+4 (55.1)	-2 (28.2)	+4 (57.1)	-1 (21.7)	+4 (70.2)	-3 (32.1)	+4 (79.9)
E. multifasciata	M1	A	ns	+3 (40.2)	ns	+3 (32.6)	ns	+4 (43.0)	ns	+3 (39.0)	ns	+2 (27.8)
		B	ns	+4 (68.8)	ns	+3 (59.2)	ns	+4 (72.9)	ns	+4 (70.1)	ns	+3 (64.5)
	M2	A	ns	+4 (54.7)	-1 (18.7)	+4 (56.1)	-1 (18.5)	+4 (58.6)	ns	+4 (62.6)	ns	+4 (52.0)
		B	ns	+1 (38.4)	ns	+3 (61.6)	ns	+3 (53.3)	ns	+4 (73.1)	ns	+4 (71.3)
		C	ns	+4 (77.4)	-3 (58.9)	+4 (75.3)	-1 (39.1)	+4 (78.8)	-1 (35.6)	+3 (65.6)	ns	+2 (44.1)
		D	ns	+1 (42.4)	ns	+3 (60.5)	ns	+3 (53.0)	ns	+3 (67.3)	ns	+3 (60.9)

Table 8.5 (cont.) Correlation levels of rainfall (R) (mm) and mean temperature (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date.									
			0-14 days		14-28 days (14 day lag)		28 days		14-42 days (14 day lag)		28-56 days (28 day lag)	
			R	T	R	T	R	T	R	T	R	T
I. palustris	M1	A	ns	-4 (64.7)	ns	-4 (63.9)	ns	-4 (70.7)	ns	-4 (64.9)	ns	-4 (51.3)
		B	ns	-3 (62.1)	ns	-3 (53.1)	ns	-3 (65.4)	ns	-3 (60.3)	ns	-3 (51.2)
	M2	A	ns	-4 (61.0)	+3 (29.8)	-4 (71.6)	+3 (29.9)	-4 (68.4)	+1 (22.0)	-4 (72.1)	ns	-4 (61.6)
		B	ns	-4 (74.5)	ns	-4 (78.0)	ns	-4 (79.1)	ns	-4 (73.5)	ns	-4 (60.3)
		C	+3 (51.2)	-3 (56.7)	+3 (61.0)	-4 (75.5)	+4 (69.6)	-3 (67.2)	+1 (39.2)	-4 (81.8)	+1 (34.6)	-4 (72.6)
		D	ns	-4 (74.5)	ns	-4 (76.5)	ns	-4 (76.2)	ns	-4 (70.3)	ns	-3 (52.9)
	E	A	+1 (9.7)	-4 (52.7)	ns	-4 (59.3)	+3 (15.8)	-4 (55.0)	+1 (9.9)	-4 (38.5)	+3 (19.0)	-4 (49.2)
		B	ns	-3 (65.2)	ns	-3 (64.8)	ns	-3 (66.7)	ns	-1 (39.3)	ns	-3 (53.5)
		C	ns	-4 (48.4)	ns	-4 (51.1)	ns	-4 (47.7)	ns	-3 (35.6)	+1 (20.0)	-3 (40.9)
		D	ns	-1 (33.2)	ns	ns	ns	ns	ns	ns	ns	ns
		E	ns	-3 (65.2)	ns	-3 (65.3)	ns	-3 (64.7)	ns	ns	ns	-3 (51.0)
		F	ns	-4 (46.0)	ns	-4 (47.9)	ns	-4 (43.6)	ns	-2 (28.0)	ns	-3 (35.9)
	FL	A	+2 (15.5)	-4 (46.4)	+3 (23.8)	-4 (44.6)	+4 (38.6)	-4 (46.2)	+4 (31.0)	-4 (46.3)	+2 (15.3)	-4 (38.7)
		B	ns	-1 (42.0)	ns	-1 (39.0)	+2 (44.5)	-1 (42.1)	ns	-1 (41.8)	ns	ns
		C	+1 (20.8)	-3 (39.3)	ns	-3 (32.4)	+4 (42.7)	-3 (37.8)	+2 (25.5)	-3 (34.0)	ns	-2 (27.1)
		D	ns	-1 (42.4)	ns	-1 (38.0)	+2 (35.2)	-1 (43.2)	ns	-1 (35.7)	+1 (42.1)	ns

Table 8.5 Correlation levels of rainfall (R) (mm) and mean temperature (cont.) (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date. 0-14 days R	0-14 days T	14-28 days (14 day lag) R	14-28 days (14 day lag) T	28 days R	28 days T	14-42 days (14 day lag) R	14-42 days (14 day lag) T	28-56 days (28 day lag) R	28-56 days (28 day lag) T
I. palustris	FL	E	ns (58.3)	-3	ns (56.3)	-3	ns (57.6)	-3	ns (54.2)	-3	ns (48.9)	-2
		F	ns (49.4)	-4 (23.0)	+1 (46.3)	-4 (29.3)	+3 (49.7)	-4 (29.2)	+3 (43.7)	-4 (26.1)	+2 (36.3)	-3
I. notabilis	M2	A	+3 (41.8)	ns	ns	ns	+3 (29.4)	ns	ns	ns	+2 (24.9)	ns
		B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		C	+3 (54.9)	ns	ns	ns	ns	ns	ns	ns	+1 (33.3)	-1 (38.5)
		D	ns	ns	ns	ns	ns	ns	ns	ns	+1 (40.8)	-1 (49.2)
	E	A	+1 (9.9)	ns	ns	-1 (9.3)	+1 (10.3)	ns	ns	ns	ns	ns
		B	ns	ns	ns	ns	+2 (44.1)	ns	ns	ns	ns	ns
		C	ns	ns	ns	ns	+1 (18.3)	ns	ns	ns	ns	ns
		D,E,F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	FL	A	ns	ns	ns	ns	+2 (13.4)	ns	ns	ns	ns	ns
		B	+2 (47.8)	ns	ns	ns	+2 (43.5)	ns	ns	ns	ns	ns
		C	+1 (23.5)	ns	ns	ns	+3 (37.2)	ns	+1 (19.5)	ns	ns	ns
		D	ns	ns	ns	ns	+2 (35.8)	ns	ns	ns	ns	ns
		E	ns	+1 (39.1)	ns	+1 (42.8)	ns	+1 (42.4)	ns	+1 (39.2)	ns	+1 (36.0)
		F	ns	ns	ns	+1 (19.3)	ns	ns	ns	+1 (20.2)	ns	+2 (25.4)

Table 8.5 (cont.) Correlation levels of rainfall (R) (mm) and mean temperature (T) (°C) with numbers of surface-active Collembola at monitored sites.

Species	Site*	Monthly sample period	Significant levels for period over which parameters measured prior to each sample date. 0-14 days		14-28 days (14 day lag)		28 days		14-42 days (14 day lag)		28-56 days (28 day lag)	
			R	T	R	T	R	T	R	T	R	T
C. thermophilus	M1	A	ns	-2 (26.7)	ns	-2 (24.6)	ns	-2 (26.7)	ns	-1 (21.2)	ns	ns
		B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	M2	A	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		B	ns	+2 (44.9)	ns	+3 (52.2)	ns	+2 (47.8)	ns	+2 (47.9)	ns	+1 (41.5)
		C	ns	ns	ns	-1 (34.5)	ns	-1 (34.6)	ns	-1 (36.1)	ns	ns
		D	ns	+3 (60.4)	ns	+4 (73.7)	ns	+3 (63.9)	ns	+3 (56.8)	ns	+1 (38.0)
	E	A,B,C, D,F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		E	-1 (41.6)	+1 (37.6)	ns	+2 (46.2)	-1 (33.8)	+2 (43.4)	ns	+2 (47.3)	ns	+3 (52.2)
	FL	A	ns	+1 (12.1)	ns	+2 (17.4)	ns	+2 (17.1)	ns	+3 (20.9)	ns	+3 (24.7)
		B	ns	ns	ns	ns	ns	ns	ns	ns	ns	+1 (37.1)
		C	ns	ns	ns	+2 (25.8)	ns	+1 (22.3)	ns	+3 (31.7)	ns	+3 (39.2)
		D	ns	ns	ns	ns	ns	ns	ns	+1 (40.9)	ns	+2 (47.2)
		E	ns	+3 (58.1)	-1 (38.2)	+3 (63.6)	ns	+3 (64.1)	ns	+4 (76.4)	ns	+4 (73.1)
		F	ns	+3 (30.7)	ns	+4 (45.5)	ns	+3 (40.8)	ns	+4 (56.1)	ns	+4 (58.3)
B. platensis	M3	A	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

KEY TO TABLE 8.6

\+ Sample periods: A = 14.9.76 - 21.4.80 (n = 44); B = 17.1.77 - 20.12.77 (n = 12); C = 17.1.77 - 18.12.78 (n = 24); D = 23.1.78 - 18.12.78 (n = 12); E = 22.1.79 - 18.12.79 (n = 12); F = 23.1.78 - 18.12.79 (n = 24).

++ Significance levels : 1 = $0.05 > P > 0.02$
2 = $0.02 > P > 0.01$
3 = $0.01 > P > 0.01$
4 = $P < 0.01$

+++ Signs indicate positive or negative regression; figures in brackets are coefficients of determination.

Table 8.6 Correlation levels of the rainfall:evaporation (R/E) ratio with numbers of surface-active Collembola at Elliott.

Species	Monthly sample period	Significance levels for periods over which P/E ratio measured prior to each sample date. 0-14 days	14-28 days (14 day lag)	28 days	14-42 days (14 day lag)	28-56 days (28 day lag)
S. pumilis	A,C,D, E,F	ns	ns	ns	ns	ns
	B	ns	ns	+1 (42.5)	ns	ns
K. australis	A	+1 (10.1)	+3 (16.5)	+3 (21.4)	+4 (24.7)	+2 (13.8)
	B	ns	ns	+2 (44.5)	ns	ns
	C	ns	ns	+1 (19.4)	+1 (22.4)	ns
	D,E	ns	ns	ns	ns	ns
	F	ns	+1 (20.1)	ns	+2 (26.1)	ns
K. oceanica var schoetti	A,B,C, D,E,F	ns	ns	ns	ns	ns
S. elegans	A,B,D, E,F	ns	ns	ns	ns	ns
	C	ns	+1 (18.9)	ns	+1 (17.9)	ns
B. viridescens	A	-3 (21.0)	-1 (10.3)	-4 (24.7)	-3 (16.8)	-1 (9.3)
	B	ns	ns	ns	-3 (54.2)	-3 (58.4)
	C	-3 (33.9)	-1 (19.9)	-4 (44.6)	-3 (41.8)	-3 (35.6)
	D	-2 (50.0)	-1 (40.4)	-4 (67.8)	-1 (38.9)	-1 (34.5)
	E	ns	ns	ns	ns	ns
	F	-1 (23.7)	ns	-2 (27.6)	ns	ns

Table 8.6 (cont.) Correlation levels of the rainfall:evaporation (R/E) ratio with numbers of surface-active Collembola at Elliott.

Species	Monthly sample period	Significance levels for periods over which P/E ratio measured prior to each sample date. 0-14 days	14-28 days (14 day lag)	28 days	14-42 days (14 day lag)	28-56 days (28 day lag)
S. viridis	A	ns	+3 (16.4)	+3 (19.8)	+4 (26.6)	+3 (17.3)
	B	ns	ns	+1 (37.1)	+1 (33.4)	ns
	C	ns	+1 (22.5)	+1 (23.3)	+3 (32.4)	ns
	D,E	ns	ns	ns	ns	ns
	F	ns	ns	ns	+2 (26.5)	+1 (17.9)
I. palustris	A	+2 (14.7)	+4 (24.5)	+4 (30.3)	+4 (35.3)	+4 (28.3)
	B	+1 (34.0)	ns	+3 (54.5)	+2 (45.1)	ns
	C	ns	ns	+2 (26.6)	+3 (31.8)	+1 (22.9)
	D	ns	ns	ns	ns	ns
	E	ns	+1 (42.6)	+1 (40.2)	+2 (44.0)	ns
	F	ns	+2 (26.2)	+1 (22.9)	+3 (29.4)	+1 (21.4)
E. marginata	A	-1 (11.1)	ns	-1 (11.5)	-3 (18.6)	-4 (38.4)
	B	ns	ns	ns	ns	ns
	C	ns	ns	ns	-1 (17.9)	-3 (39.0)
	D	ns	ns	-1 (36.8)	ns	-3 (63.9)
	E	-2 (45.5)	ns	ns	-1 (37.8)	-4 (68.1)
	F	-2 (24.9)	ns	-1 (23.8)	-2 (27.2)	-4 (54.5)

Table 8.6 (cont.) Correlation levels of the rainfall:evaporation (R/E) ratio with numbers of surface-active Collembola at Elliott.

Species	Monthly sample period	Significance levels for periods over which P/E ratio measured prior to each sample date. 0-14 days	14-28 days (14 day lag)	28 days	14-42 days (14 day lag)	28-56 days (28 day lag)
I. notabilis	A,B,C, D,E,F	ns	ns	ns	ns	ns
C. thermophilus	A,B,C, D,F	ns	ns	ns	ns	ns
	E	-4 (69.7)	ns	-1 (48.9)	-1 (33.2)	-2 (49.6)

CHAPTER 9

A SURVEY OF SURFACE-ACTIVE COLLEMBOLA IN TASMANIAN FIELD CROPS AND APPRAISAL OF THEIR ACTIVITY AND PEST STATUS

INTRODUCTION

In Tasmania, surface-active species of Collembola are often associated with damage to the seedling stage of the oil poppy, Papaver somniferum, spring sown crops in the northern areas of the State being particularly susceptible. Statewide an average of 5.6% of sown crops are currently being sprayed annually for the control of the lucerne flea, Sminthurus viridis (L.) and 5.4% for other unidentified globular species (Lewis pers. comm.). In addition, a number of other seedling field crops are occasionally reported as being damaged by Collembola other than S. viridis, following sowings in late winter and early spring (Green pers. comm.).

Womersley (1932, 1939) recorded several collembolan species from Tasmanian agricultural areas (see Chapter 1), some of which have been recorded as pests overseas (Collinge (1909, 1910); Theobald (1911); Mills (1930); Folsom, (1933); Paclt (1956) and appeared on Womersley's own (1939) list of injurious species. Collections of Collembola from local field crops from 1975-1989 have enabled further examination of this fauna, and these, together with laboratory feeding studies, have provided additional information on their seasonality and pest status. This Chapter presents the results of these investigations and (i) identifies the surface-active Collembola that are commonly found in Tasmanian field crops, with particular reference to those sown during late winter and early spring, (ii) examines their distribution, (iii) compares the species found in field crops with those in pasture and (iv) discusses their activity and pest status.

MATERIALS AND METHODS

(i) Pitfall trapping

Traps were placed in oil poppy crops sown in Krasnozem soils on three properties at Wesley Vale near Devonport, north-west Tasmania.

Site 1: crop sown August 6, 1982; traps set on August 20 at the cotyledon growth stage.

Site 2: crop sown August 16, 1982; traps set on August 16 prior to emergence.

Site 3: crop sown August 13, 1982; traps set on September 2 at the cotyledon/2-leaf growth stage.

An area of 30 m x 30 m was selected near the centre of each paddock and divided into 9 sub-plots (10 m x 10 m) with a single trap being placed randomly in each. The type of trap used was similar to that described by Majer (1978) and consisted of a Corning Pyrex test tube (no. 9820) (internal diameter 16 mm, external diameter 18 mm, depth 150 mm) inserted into a PVC sleeve (internal diameter 18 mm, external diameter 21 mm, depth 160 mm). Soil was removed using a hollow steel boring tool with a pointed end and an external diameter equivalent to the PVC sleeve; this was driven into the ground with a mallet. Once the sleeve was in place

the tube containing a few ml of 90% alcohol and a few drops of glycerol was inserted following external smearing with petroleum jelly to facilitate its removal from the sleeve.

Traps were emptied fortnightly until December 8, 1982, the final sample being taken 4 weeks later on January 5, 1983. Individual traps were emptied separately into screw-cap glass jars (6 cm high, 6 cm diameter) and returned to the laboratory where the Collembola were identified and counted. Meterological data for the trapping period was obtained from the nearest weather station (East Devonport).

(ii) Surveys

About 61% of field crop collections were obtained by suction sampling according to the method described in Chapter 2. Of these, 77% were examined for all collembolan species present, the remainder being isolated collections carried out for the purpose of sampling one or two species when observed in large numbers. The remaining 39% of other samples were either collected by pitfall trap, sweep net or pooter or were submitted for identification by field officers or members of the public to the Entomology Section of the Tasmanian Department of Primary Industry. A few previously identified specimens that had been collected from field crops back to 1953 and deposited in the collection were included with the survey data. The majority of the collections (54%) were from oil poppies, the other field crops sampled included broad beans, peas, carrots, onions, sugar beet, lucerne, wheat, cucurbits and brassicas. About 77% of samples were taken in July-November, which includes the period when oil poppies and most of the other field crops grown in the State are in the vulnerable seedling stage. A summary of field crop sample periods is presented in Table 9.1. Data for species occurrence in pasture (Chapter 8) was compared with collection data from field crops (miscellaneous collections were not included) to determine any possible habitat preferences. Species were then categorised according to their relative level of occurrence in each habitat.

As was done in Chapter 8 for pastures, field crops were classified as high and low rainfall ecotypes around the 800 mm isohyet. The survey data was then used to determine possible species preference for each ecotype. Significance levels were determined using the chi-squared test and the results were compared with those obtained from the analyses carried out on the surface-active pasture fauna.

(iii) Feeding observations

Examination of crops for Collembola damage was carried out during field surveys and at pitfall sites. Additional feeding observations were carried out in the laboratory as follows:

Oil poppy seeds were washed with 1% sodium hypochlorite solution and germinated on moist muslin cloth. Once the radicles appeared, the

Table 9.1 Summary of field crop collections (1953-1989).

Collection method	No. of collections per month												Total collections
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
Suction sample surveys*	8	0	0	0	1	1	8	9	11	14	6	-	58
Pitfall trapping*	3	0	0	0	-	-	1	1	9	6	6	3	29
Miscellaneous collections**	1	2	1	0	2	2	4	1	4	7	9	4	37

* All collembolan species identified in sample

**Includes 18 suction samples in which not all species identified

germinating seedlings were placed in observation cultures. These consisted of covered pyrex crystalizing dishes (height 5.4 cm, diameter 9.2 cm). Filter paper (Whatman 541, 9 cm) was used to line the base of each container on which was placed a saturated wad of folded facial tissue (ca. 5.5 x 7.5 cm) with four seedlings, their developing root systems being covered by strips of tissue kept moist with Hoaglands solution (Fig. 9.1). A second culturing technique was also used (Fig. 9.2). Sieved unsterilised soil (pH 7.1) selected from a market garden (where B. hortensis was active) was placed in the pyrex dishes to a depth of 2 cm. Seedlings (4 per dish) were planted, with Collembola being added 3-4 days later. The soil was kept moist throughout the observation period.

Feeding tests were carried out with field collected species selected either because they or related species were common in local crops during surveys and/or because of their (or related species) previous associations with primary damage to other plants, either in Australia or overseas. Adults and older nymphs of collembolan species tested were placed in a series of separate cultures with plants of two age groups: newly emerged seedlings at the early cotyledon stage and older plants ranging from the 2-leaf to 4-leaf growth stages, there usually being at least 6 replicates of each age group per species in each series and 2 controls.

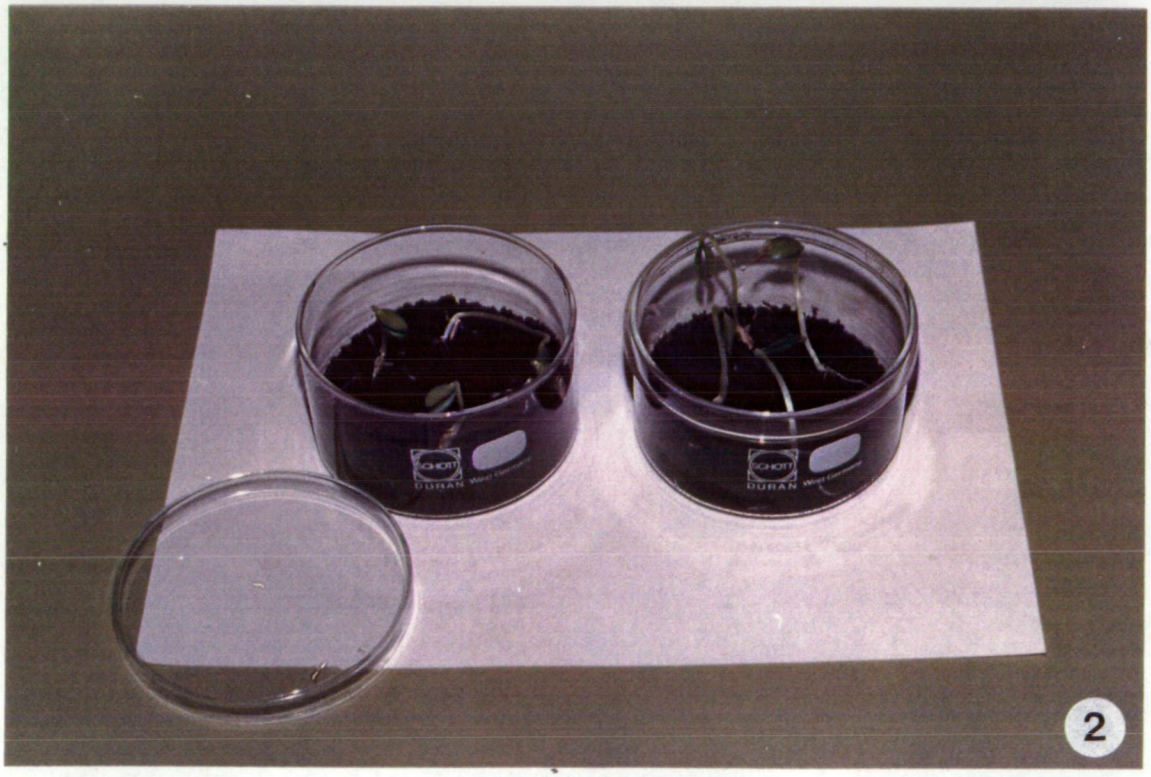
An assessment of the secondary feeding habits of some species was also made by allowing seedlings (ranging from the cotyledon to the 4-leaf stage) to die. Once breakdown had commenced, 4 decaying seedlings, kept permanently moist, were placed in similarly replicated cultures.

Feeding damage by each collembolan was estimated by visual assessment of each plant. Cultures were usually terminated after 6-7 days if no signs of feeding were apparent. However, length of the culturing period often varied for each species depending on their voracity for live and dead plant material and their size in relation to the amount of plant material available for consumption. Several replicate trials of the above tests were carried out in some cases if no feeding was initially observed in a culture series for a species previously suspected of damaging live plants. Although a constant number of Collembola were used to infest each culture for each trial, arbitrary infestation levels of 25, 50 and 100 individuals per culture were used in separate trials.

Additional feeding studies using the above method, were carried out to observe the feeding behaviour of collembolan species on carrots (a common Tasmanian field crop) cucumbers, cotton (Gossypium sp.) and subterranean clover (T. subterraneum). The latter two plants were selected to test some previously reported but isolated instances of damage. These included Katianna australis reported as injurious to T. subterraneum (Womersley 1939; Wallace and McKerras 1970) and Entomobrya unostrigata

Figs 9.1-9.2 Culture techniques used for collembolan feeding observations : (1) culture without soil; (2) culture with soil.


1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recorded damaging cotton, Gossypium sp. by Owen and Owen (1958).

RESULTS

(i) Identification and activity

Table 9.2 lists the 26 surface-active species representing 6 families that were identified in field crops, together with the total records for each species. Spring and early summer activity as indicated by pitfall catches is also shown for species identified at the trap sites.

Only the two Katianna species listed are native, and although the origin of J. stachi australiensis is uncertain (Greenslade pers. comm.), the remainder are introductions and probably cosmopolitan in distribution (see Chapter 13).

Examination of Table 9.2 shows that the most frequently recorded species in crops have been S. viridis, B. hortensis, B. viridescens, J. stachi australiensis, P. quinquefasciatus (Sminthuridae), E. marginata (Entomobryidae), I. palustris and C. thermophilus (Isotomidae), H. vernalis (Hypogastruridae) and B. platensis (Neanuridae). A total of 19 species were caught in pitfall traps. However, the activity of 12 of these was classed either as low or as in the case of S. pumilis, K. australis, I. tigrina, H. gibbosa and H. viatica, very low with the total capture for each of these not exceeding 6 specimens throughout the trapping period. The remaining 7 species (B. hortensis, B. viridescens, P. quinquefasciatus, I. palustris, C. thermophilus, H. vernalis and B. platensis) were the most abundant. They were identified at all sites and showed high levels of activity in at least one instance.

Activity at the pitfall sites was greatest during September from the commencement of sampling, with crop growth ranging from the cotyledon to the 8-leaf stage during this period. Numbers of most species showed a general tendency to decrease as the crop developed and as temperatures increased and rainfall decreased, although there were some substantial falls of rain later, during December (Fig. 9.3). The only species to show any large increases in activity with time was P. quinquefasciatus which commenced hatching after trapping commenced, the first appearance of young nymphs being in mid-late September (sites 1 and 2) and October (site 3). Moderate to high activity for this species was recorded at all sites from November to January when the crop was well advanced. In pasture, this species showed a distinct summer maximum (Chapter 8) with nymphs first appearing in November. The results here suggest P. quinquefasciatus is active in field crops for a longer period. A slight increase in numbers was recorded for E. marginata at all sites, although activity remained low.

A comparison of the percent occurrence of collembolan species in field crop and pasture together with the habitat category of each is presented in Table 9.3. Of the 40 species listed, 9 were classified as having a high level of occurrence in both pasture and crop, 10 with a frequency of

Table 9.2 Surface-active Collembola identified in Tasmanian field crops (1975-1989) and assessment of species activity in spring/early summer from pitfall traps in oil poppy crops (September 1982-January 1983).

Species	Total collection records	Pitfall site where active	Activity assessment rating+								
			2/9	16/9	28/9	13/10	26/10	9/11	24/11	8/12	5/1
Dicyrtomidae	1	NR*	-	-	-	-	-	-	-	-	-
cf. Dicyrtomina sp.											
Sminthuridae											
Sphaeridia pumilis (Krausbauer)											
group	4	1	L1	0	0	0	0	0	0	0	0
Jeannenotia stachi australiensis											
Betsch and Massoud	20	1	L1	L1	L1	0	0	0	0	0	L1
		2	L1	L1	0	L1	0	0	0	0	0
		3	-	L1	L1	L1	0	L1	0	0	0
Katianna australis Womersley	10	3	-	L1	L1	0	0	0	0	0	0
Katianna sp. oceanica var.											
schoetti Womersley	3	NR*	-	-	-	-	-	-	-	-	-
Sminthurinus elegans (Fitch)	6	NR*	-	-	-	-	-	-	-	-	-
Prorastriopes quinquefasciatus	34	1	0	0	L1	L2	M	M	M	L2	L1
(Krausbauer)		2	0	0	L1	M	M	H	M	M	H
		3	-	0	0	L2	L2	M	M	M	M
Deuterosminthurus sulphureus											
mediterraneus Ellis	4	NR*	-	-	-	-	-	-	-	-	-
Bourletiella hortensis (Fitch)	50	1	L1	L1	L1	L1	L1	0	0	0	0
		2	L1	L1	L1	M	M	L2	L2	L1	L1
		3	-	H	H	H	M	L2	L1	L1	L1
Bourletiella viridescens Stach	59	1	L1	L1	L1	L1	0	0	0	0	0
		2	L1	L1	L1	L1	L1	L1	L1	0	0
		3	-	H	H	H	M	L2	L1	0	L1
Sminthurus viridis (L.)	38	1	L2	L1	L1	L1	0	0	0	0	0
		3	-	0	0	L1	0	0	0	0	0
Entomobryidae											
Entomobrya sp. cf. lanuginosa											
(Nicolet)	3	NR*	-	-	-	-	-	-	-	-	-

Table 9.2 Surface-active Collembola identified in Tasmanian field crops (1975-1989) and assessment of species activity (cont.) in spring/early summer from pitfall traps in oil poppy crops (September 1982-January 1983).

Species	Total collection Records	Pitfall site where active	Activity assessment rating+ 2/9	16/9	28/9	13/10	26/10	9/11	24/11	8/12	5/1
Entomobrya marginata (Tullberg)	43	1	L1	L1	L1	L1	L1	L1	L1	L1	L1
		2	L1	0	L1	L1	L1	L1	L1	L1	L1
		3		L1	L1	L1	L1	L1	L1	L1	L1
Entomobrya multifasciata (Tullberg)	13	NR*	-	-	-	-	-	-	-	-	-
Entomobrya unostrigata Stach	9	NR*	-	-	-	-	-	-	-	-	-
Isotomidae											
Isotomurus palustris (Mueller) group	43	1	H	H	M	L1	L1	0	0	0	0
		2	L1	L1	L1	L1	L1	L1	0	0	0
		3	-	M	M	M	M	L1	0	0	0
Isotoma tigrina (Nicolet)	7	2	L1	0	0	L1	0	0	0	0	0
		3	-	L1	L1	0	0	0	0	0	0
Cryptopygus thermophilus (Axelson)	20	1	H	H	H	H	H	L1	L1	0	0
		2	0	0	0	L1	L1	0	0	0	0
		3	-	0	L1	L1	L1	L1	L1	L1	L2
Hypogastruridae											
Hypogastrura (Ceratophysella) denticulata (Bagnall)	14	1	L1	L1	L1	L1	L1	0	0	0	0
		3	-	L1	L1	L1	L1	L1	L1	0	0
Hypogastrura (C.) sp. cf. engadinensis Gisin	7	1	L1	L1	0	0	L1	0	0	0	0
		3	-	0	0	0	L1	0	0	0	0
Hypogastrura (C.) gibbosa (Bagnall)	1	2	0	0	0	L1	0	0	0	0	0
Hypogastrura (Hypogastrura) manubrialis (Tullberg)	11	2	L1	L1	L1	0	0	0	0	0	0
		3	-	L1	L1	L1	L1	0	0	0	L1
Hypogastrura (H.) vernalis (Carl)	27	1	L1	0	0	0	0	0	0	0	0
		2	H	M	M	M	M	L2	L1	L1	M
		3	-	L1	L1	L1	0	0	0	0	0
Hypogastrura (H.) viatica (Tullberg)	3	3	-	L1	0	0	0	0	0	0	0

Table 9.2 Surface-active Collembola identified in Tasmanian field crops (1975-1989) and assessment of species activity (cont.) in spring/early summer from pitfall traps in oil poppy crops (September 1982-January 1983).

Species	Total collection records	Pitfall site where active	Activity assessment rating+								
			2/9	16/9	28/9	13/10	26/10	9/11	24/11	8/12	5/1
Xenylla sp.	1	NR*	-	-	-	-	-	-	-	-	-
Neanuridae											
Brachystomella platensis Najt	46	1	H	M	M	L2	L1	L1	L1	L1	L1
and Massoud		2	M	L2	L2	M	M	L2	L1	L1	M
		3	-	L2	L2	L2	L2	0	0	0	L1

+ Activity rating (species mean no./trap): 0 = no activity recorded; L1 = very low activity (<7 per trap); L2 = low activity (7-20 per trap); M = moderate activity (20-100 per trap); H = high activity (>100 per trap).

NR* = species not recorded at any pitfall site.

Fig. 9.3 Rainfall and mean temperature for East Devonport (September 1982 - January 1983).

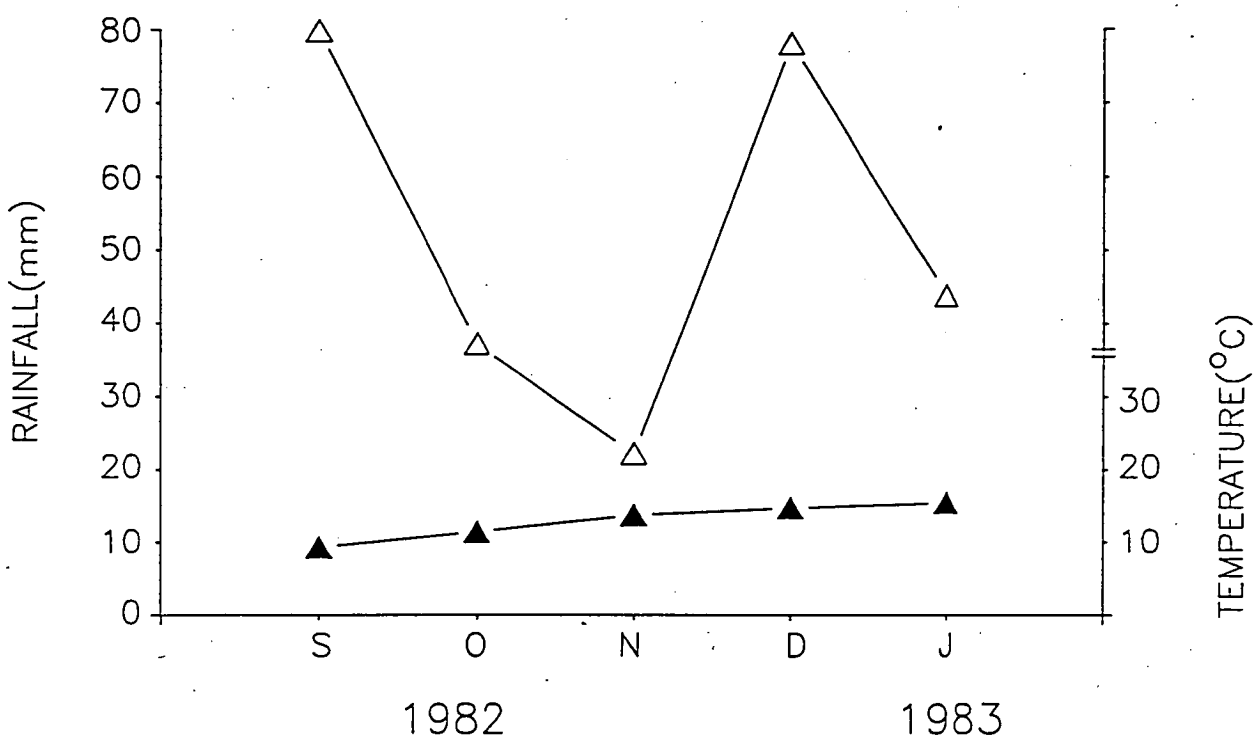

RAINFALL(mm)
80
70
60
50
40
30
20
10
0
TEMPERATURE(°C)
30
20
10
S
O
N
D
J
1982
1983

Table 9.3 Comparison of occurrence of surface active collembolan species in pastures and field crops and estimated preference for each habitat.

Species	% Pastures in which identified (n=239)	% Field crops in which identified (n=87)	Habitat+ preference
Dicyrtomidae			
cf. Dicyrtomina sp.	3.4	0.9	4
Sminthuridae			
Sminthurides sp.	2.5	0	4
Sphaerida pumilis (Krausbauer) group	48.1	5.2	2
Jeannenotia stachi australiensis Betsch and Massoud	5.0	25.9	3
Katianna australis Womersley	38.5	10.4	2
Katianna mucina Womersley	5.0	0	2
Katianna sp. cf. obscura (Womersley) comb. n.	0.4	0	4
Katianna oceanica var. schoetti Womersley	47.7	2.6	2
Katianna ornata Womersley	1.7	0	4
Katianna sp. 1	19.3	0	2
Sminthurinus elegans (Fitch)	35.6	5.2	2
Sminthurinus mime Boerner	0.4	0	4
Sminthurinus tuberculatus Delamare and Massoud	1.7	0	4
Deuterosminthurus sulphureus mediterraneus Ellis	3.4	1.7	4
Prorastriopes quinquefasciatus (Krausbauer)	2.9	46.8	3
Bourletiella hortensis (Fitch)	0.4	53.7	3
Bourletiella viridescens Stach	51.5	58.6	1
Corynephoria sp. cf. vulgaris	0.004	0	4
Sminthurus viridis (L.)	23.4	32.8	1
Entomobryidae			
Entomobrya sp. cf. lanuginosa (Nicolet)	20.5	2.6	2
Entomobrya marginata (Tullberg)	58.2	57.8	1
Entomobrya multifasciata (Tullberg)	50.2	10.6	2
Entomobrya unostrigata Stach	2.9	8.7	3
Lepidocyrtus sp.	1.7	0	4

Table 9.3 (cont.) Comparison of occurrence of surface active collembolan species in pastures and field crops and estimated preference for each habitat.

Species	% Pastures in which identified (n=239)	% Field crops in which identified (n=87)	Habitat+ preference
Isotomidae			
Isotoma tigrina (Nicolet) group	16.3	9.5	1
Isotomurus palustris (Mueller) group	65.7	49.5	1
Isotoma notablis (Schaeffer)	9.2	0	2
Cryptopygus thermophilus (Axelson)	24.3	32.0	1
Hypogastruridae			
Hypogastrura (Ceratophysella) denticulata (Bagnall)	12.1	21.6	1
Hypogastrura (C.) sp. cf. engadinensis Gisin	11.3	10.3	1
Hypogastrura (C.) gibbosa (Bagnall)	0.8	1.7	4
Hypogastrura (Hypogastrura assimilis (Krausbauer)	2.1	0	4
Hypogastrura (H.) manubrialis (Tullberg)	6.3	16.4	3
Hypogastrura (H.) purpurescens (Lubbock)	0.4	0	4
Hypogastrura (H.) vernalis (Carl)	11.7	33.7	3
Hypogastrura (H.) viatica (Tullberg)	0	1.7	4
Xenylla sp.	0	0.9	4
Triacanthella sp.	1.3	0	4
Neanuridae			
Brachystomella platensis Najt and Massoud	36.4	56.9	1

+ Habitat preference category: 1 = relatively high level of occurrence in both pasture and field crops (no apparent preference for either habitat); 2 = frequency of occurrence higher in pasture (suggesting apparent preference for this habitat over field crops); 3 = frequency of occurrence higher in field crops (suggesting apparent preference for this habitat over pasture); 4 = species uncommon in both habitats.

occurrence higher in pasture, 6 with a frequency of occurrence higher in crop with the remaining 15 species being classified as uncommon in both habitats. H. viatica and Xenylla sp. (Hypogastruridae) were the only species identified in crops (in small numbers) that were not identified in pastures. Locations where each species was identified during crop surveys are shown on the maps presented in Figs 9.4-9.29.

Table 9.4 compares the frequency of species occurrence in field crops sampled in wet and dry areas and compares the results with that obtained in pasture. Of the 26 species identified in field crops, the results show that six species, B. hortensis, B. viridescens, E. marginata, C. thermophilus, H. denticulata and H. manubrialis were more common in crops in high rainfall areas; E. multifasciata was more common in crops sampled in drier areas. A further 6 species, J. stachi australiensis, P. quinquefasciatus, S. viridis, I. palustris, H. vernalis and B. platensis exhibit no clear preference for crops in either area. Of the remaining 13 species, frequency of occurrence in crops was too low to use significant levels as an indicator of preference. Examination of Table 9.4 shows that J. stachi australiensis, P. quinquefasciatus, B. viridescens and E. multifasciata have the same level of preference for pastures in wet and dry areas as for field crops. Additionally, S. viridis and I. palustris exhibit a clear preference for pastures in wet areas ($P<0.01$) but the level of preference for field crops in wet or dry areas was not significant ($P>0.05$), although the frequency of occurrence of both species was higher in crops surveyed in areas of high rainfall. Comparison of the results obtained for E. marginata, C. thermophilus, H. denticulata, H. manubrialis, H. vernalis and B. platensis all of which are hemiedaphic species, show a variation in trends between crops and pastures sampled in wet and dry areas.

(ii) Feeding Observations

Trap sites - At sites 1 and 2 no feeding damage to oil poppies attributable to surface-active Collembola was noted either on stems, cotyledons or leaves. Table 9.2 shows that I. palustris, C. thermophilus, and B. platensis were the most active species at site 1 with moderate to high activity recorded for these species up to September 28 at least to the 8-leaf to 10-leaf growth stage. At site 2, H. vernalis and B. platensis were initially the most active species up to the 2-leaf stage, although moderate activity of B. hortensis was recorded from the 8-leaf through to the 12-leaf stage and P. quinquefasciatus became active from the 6-leaf to 8-leaf stage. At site 3, high mixed populations of B. hortensis and B. viridescens estimated at between 3000 to 5000/m^2 were active when the traps were set, the crop age ranging from the cotyledon to the 2-leaf stage. No damage that could be attributed to these Bourletiella spp. was noted and the crops did not appear to be adversely affected by their activity, which was recorded at high levels up to the 10-leaf stage of growth. Yields from these crops were average for the district.

Table 9.4 Comparison of occurrence of surface-active Collembola between field crops and pasture of low and high rainfall areas.

Species	Percent occurrence in samples					
	Crop			Pasture		
	High rainfall (n=55)	Low rainfall (n=29)	Sig.	High rainfall (n=150)	Low rainfall (n=89)	Sig.
Dicyrtomidae						
cf. Dicyrtomina sp.	1.8	0	n.s.	5.3	0	n.s.
Sminthuridae						
S. pumilis	5.4	3.4	n.s.	52.0	41.6	n.s.
J. stachi australiensis	23.2	24.1	n.s.	6.0	3.4	n.s.
K. australis	14.3	6.9	n.s.	50.7	18.0	**
K. oceanica var. schoetti	5.4	0	n.s.	58.0	30.3	**
S. elegans	3.6	13.8	n.s.	36.7	33.7	n.s.
D. sulphureus mediterraneus	0	6.9	n.s.	3.3	5.6	n.s.
P. quinquefasciatus	42.9	31.0	n.s.	1.3	5.6	n.s.
B. hortensis	71.4	0	**	0.7	0	n.s.
B. viridescens	75.0	20.7	**	59.3	38.2	**
S. viridis	42.9	27.6	n.s.	30.7	11.2	**
Entomobryidae						
E. lanuginosa	1.8	6.9	n.s.	18.0	24.7	n.s.
E. marginata	60.7	24.1	**	57.3	59.6	n.s.
E. multifasciata	3.6	34.5	**	42.0	64.0	**
E. unostrigata	7.1	17.2	n.s.	0	7.9	**
Isotomidae						
I. palustris	53.6	34.5	n.s.	72.0	55.0	**
I. tigrina	10.7	3.4	n.s.	25.3	1.1	**
C. thermophilus	33.9	0	**	24.7	23.6	n.s.
Hypogastruridae						
H. (C.) denticulata	21.4	0	**	11.3	13.5	n.s.
H. (C.) engadinensis	8.9	3.4	n.s.	6.0	20.2	**
H. (C.) gibbosa	1.8	0	n.s.	0	0	n.s.
H. (H.) manubrialis	17.9	0	**	1.3	14.6	**
H. (H.) vernalis	26.8	20.7	n.s.	4.0	24.7	**
H. (H.) viatica	1.8	0	n.s.	0	0	n.s.
Xenylla sp.	0	3.4	n.s.	0	0	n.s.
Neanuridae						
B. platensis	53.6	37.9	n.s.	22.0	60.7	**

Field Surveys - The only surface-active Collembola that could be positively associated with damage to plant material during field surveys were S. viridis, B. hortensis and B. viridescens. In the south-east, damage to winter sown oil poppies by S. viridis was observed in two instances. The first recorded damage was on August 25, 1982, in a crop at the 6-leaf growth stage; this consisted of chewed leaf edges and the removal of epidermal tissue from the leaves (Fig. 9.30). Comparison with other parts of the crop in which S. viridis was absent suggested that the main affect of the damage was to retard growth. In the second instance (August 7, 1984) slight damage to the cotyledons of plants at the 2-leaf stage was noted (Fig. 9.32). Damage to spring sown oil poppies on the north-west coast, again symptomised by removal of epidermal tissue and edge chewing, was noted in a single instance on August 18, 1984, however, although the dominant species were mixed populations of B. viridescens and B. hortensis, S. viridis was also identified in smaller numbers. In all the above cited cases, sprays were used to combat infestations. Damage to lucerne by S. viridis was also recorded during field collections.

Damage attributable to B. hortensis was observed in one instance when large numbers (estimated at 4000/m^2) were recorded in a market garden at New Town on December 2, 1988. The species had inflicted severe damage to cucumber seedlings at the cotyledon stage of growth (Fig. 9.34). The main affect of the damage was probably growth retardation rather than the distruction of individual plants. Severe damage to cucumber cotyledons, attributable to mixed populations of B. hortensis and B. viridescens, was also recorded in a 1 ha crop near Lymington. In this instance, the grower applied a spray of chlorpyrifos to control the infestation. In both cases the injury was similar to that described and illustrated by Fink (1914), with tissues being completely eaten away leaving irregular holes in cotyledons and leaves. A thin transparent layer of tissue often seprated upper and lower leaf (cotyledon) surfaces.

Laboratory - There was no observable difference in species feeding levels in cultures with or without soil, therefore, only the results obtained from cultures without soil are reported. The results of these observations are shown in Table 9.5. The most voracious feeder on live plant material was S. viridis (Fig. 9.31), high consumption levels of seedlings of all plants cultured with this species being observed. The species also consumed equally high levels of decaying plant material. Bourletiella spp., Katianna spp., I. palustris and E. unostrigata were found to cause some injury to live seedling plants in culture (Figs. 9.33-9.35 and 9.37-9.38). However, examination of Table 9.5 shows that different plant species varied in susceptibility to attack: I. palustris injured cucumber, but not carrots, subterranean clover or oil poppies; E. unostrigata injured cotton but not oil poppies, subterranean clover or carrots; K. australis injured oil poppies, carrots and cotton but not

Table 9.5 Results of collembolan feeding trials on live and dead seedling plants.

Collembolan species	Plant species	No. specimens per culture	Stage of development at infestation*	Total plants observed	No. attacked	Mean consumption estimate+
B. viridescens	Oil poppy	100	1	76	2	D
			3	32	32	B
	Carrot	100	1	44	4	D
	Cucumber	100	1	24	24	B
	Subterranean clover	100	1	24	6	D
			5	24	0	E
B. hortensis	Oil poppy	100	1	72	5	D
		100	2	24	0	E
		100	4	24	24	B
	Carrot	100	1	48	3	C
	Cucumber	100	1	24	24	B
	Subterranean clover	100	1	24	6	D
			5	24	0	E
P. quinquefasciatus	Oil poppy	100	1	64	0	E
			2	32	0	E
			3	64	4	D

Table 9.5 Results of collembolan feeding trials on live and dead seedling plants. (cont.)

Collembolan species	Plant species	No. specimens per culture	Stage of development at infestation*	Total plants observed	No. attacked	Mean consumption estimate+
S. viridis	Oil poppy	50	1	120	120	A
			2	32	32	A
			3	16	16	A
	Carrot	50	1	32	32	A
	Subterranean clover	50	1	40	40	A
K. australis	Oil poppy	50	1	32	3	D
		100	1	60	29	D
		25	4	32	32	A
	Carrot	50	1	64	13	D
	Subterranean clover	50	1	96	0	E
		100	5	32	0	E
	Cotton	100	1	8	4	D
Katianna sp. 1	Oil poppy	100	1	12	11	C
		25	1	48	8	C
		25	2	44	23	D
		25	3	36	35	C
		25	4	64	57	C

Table 9.5 Results of collembolan feeding trials on live and dead seedling plants. (cont.)

Collembolan species	Plant species	No. specimens per culture	Stage of development at infestation*	Total plants observed	No. attacked	Mean consumption estimate+
I. palustris	Oil poppy	25	1	24	0	E
		50	2	24	0	E
		25	4	24	32	A
	Carrot	50	1	24	0	E
	Cucumber	50	1	48	39	C
	Subterranean clover	50	1	24	0	E
		50	5	24	0	E
E. unostrigata	Oil poppy	50	1	44	0	E
	Carrot	50	1	32	0	E
	Subterranean clover	50	1	32	0	E
	Cotton	50	1	8	8	D

*1 = newly emerged cotyledons (live plants); 2 = 2-leaf to 4-leaf stage (live plants); 3 = cotyledons (moist, dead and decaying plants); 4 = 2-leaf to 4-leaf stage (moist, dead and decaying plants); 5 = mature trifoliate leaves.

+A = feeding level high, > 40% cotyledons/leaves damaged; B = feeding level moderate, 10-40% cotyledons/leaves damaged; C = feeding level low, 2-9% of cotyledons/leaves damaged; D = very low, <2% of cotyledons/leaves damaged; E = no visible evidence of feeding.

subterranean clover and neither B. hortensis or B. viridiscens fed on sub-clover but both caused some injury to cucumbers, carrots, and oil poppies. In addition, these species were less voracious than S. viridis as demonstrated by lower feeding levels observed in the cultures (Table 9.5). Damage by Katianna and Bourletiella to oil poppies was mainly restricted to the tender, newly emerged cotyledons and consisted of the removal of small pieces of epidermal tissue and slight edge chewing, although stem pitting and edge chewing of surface tissue from newly formed first leaves was observed in some instances. Occasionally, more extensive damage resulted from chewing around tips and along edges of cotyledons causing them to become withered and distorted, but there was no indication that any seedlings would die. No evidence of feeding damage of any of these species was noted on oil poppies at the 2 to 4-leaf stages of development.

K. australis, K. sp. 1, I. palustris and E. unostrigata all fed on decaying tissues of oil poppies, and with the exception of E. unostrigata high consumption levels are recorded (Table 9.5). P. quinquefasciatus did not feed on live or decaying oil poppies. It was, however, observed grazing a fungus (Fusarium sp.) growing on the decaying plants.

DISCUSSION

(i) Species occurrence and distribution

The data presented in Table 9.3 are only used to give an indication of possible habitat preference and need careful interpretation. Other supporting data is useful in considering placement in a habitat category. For instance, the % occurrence of E. unostrigata was higher in field crop than pasture but in both cases <10% and although common in localised areas it appears to have a restricted distribution in Tasmania. However, very large numbers were observed active on the soil surface at the base of some field crops during surveys, further suggesting the species may prefer a more open habitat to a closed sward. Large numbers of this species on cultivated ground were reported in the Southern American states of Texas and New Mexico by Owen and Owen (1958). The ability of this species to survive in an open and usually drier habitat is supported by data presented in Table 9.4, which shows a significant preference for pastures in low rainfall areas as well as a tendency to favour the crop habitat in areas of low rainfall.

Variations in factors between pasture and crop habitat that influence population size such as micro-climate, competition, soil and vegetation type may have a considerable affect on some species and although 10 were placed in category 1, it cannot be concluded that each can survive equally well in both environments. Species more widespread and attaining higher numbers in pasture may have been recorded during field crop surveys on land recently ploughed from pasture, and S. viridis is frequently reported as damaging crops sown in such paddocks. In pasture it is recorded as attaining population maxima up to 51,000/m^2 (Chapters 4

and 8), however, it is unlikely that similar population levels would be attained in a more exposed field crop environment where they would be more restrained by environmental factors, such as an adverse change in weather conditions. Species in the genus Katianna, native inhabitants of grassland, are obviously better adapted to colonise a sown pasture habitat rather than the cultivated ground of a field crop. Although K. australis and K. oceanica var. schoetti, which have successfully colonised improved pastures, were occasionally found in field crops, this incidence may be more attributable to short term survival on land recently ploughed from pasture or their occasional invasion of ploughed land from nearby pasture. K. sp. cf. obscura and K. pescotti seem to have been less successful in establishing in the culture steppe than the other 5 Katianna species listed, although these may not be as widespread as the other species in their native habitat. Interspecific competition for habitat niches may be a key factor operating here as it may be in the case of the 2 Bourletiella species. Results show that B. viridescens is equally common in both pastures and field crops in areas of high rainfall, whereas B. hortensis is rare in pasture being restricted almost entirely to field crops where it has only been recorded during spring and early summer. The few instances of B. hortensis being recorded from pasture were in wetter areas, also during spring and summer (Fig. 8.21).

Comparisons of the distribution of species between crop and pasture in high and low rainfall areas (Table 9.4) show that most exhibit similar trends for each ecotype. It is interesting to note the occurrence of S. viridis in field crops in dry southern localities such as Hamilton, Orielton and Colebrook where there are no records from pasture. These isolated records suggest that suitable moisture conditions enable populations to become active from time to time probably as a result of crop irrigation or on poorly drained land after good rains. Results for hemiedaphic species such as B. platensis and H. vernalis, whose frequency of occurrence was significantly higher in pastures in low rainfall areas but exhibited no significant preference for crops in wet or dry areas, may be partly explained by the exposed crop environment of dry areas becoming a less favoured habitat for species survival. Differences in microclimate between pasture and field crop habitats may also be a key factor contributing to results obtained for E. marginata, C. thermophilus, H. denticulata and H. manubrialis, all of which showed significantly higher frequencies of occurrence in crops sampled in wet areas but were either found equally distributed between wet and dry pasture ecotypes (E. marginata, C. thermophilus and H. denticulata) or as in the case of H. manubrialis more common in pastures of low rainfall areas (see Chapter 12).

(ii) Pest status

S. viridis is the most damaging collembolan on field crops in Tasmania. This conclusion is based on the instances of field damage, together with its polyphagy, the high consumption levels of live plants in culture and

its widespread distribution. The field surveys showed that S. viridis often occurs with mixed populations of Bourletiella viridescens and B. hortensis. In some cases, therefore, where damage to oil poppies has been attribted to Bourletiella spp. by field officers, the culprit may often have been S. viridis. In these instances, S. viridis may often occur in relatively small numbers and make it more difficult to detect. Colour variations could also confuse its identification with Bourlettiella spp. in the field.

Although no field damage to seedling oil poppies was evident at the pitfall sites where B. hortensis and B. viridiscens were active in the absence of S. viridis, both species fed on a small number of oil poppy seedlings in culture, indicating that both were capable of inflicting damage to this crop in the field even if such damage is low in occurrence. Furthermore, the damage observed to seedling cucumbers by B. hortensis and B. viridescens both in the field and in culture confirms that these species can be a pest of some crops from time to time, although the culture studies showed that plant species varied in their susceptibility to attack. Differences in susceptibility of plants to attack by B. hortensis were also reported by Honma (1988). The species had been considered a pest of seedling sugar beet in Japan, however, Honma found that the species hardly fed on sugar beet in culture but caused injury to a number of other seedlings including cucumber and crucifers (raddish and rape). He concluded that the species was economically unimportant on sugar beet, although acknowledging that secondary injury following damage by a flea beetle (Chaetocnema concinna Marshall) may occur.

In the literature there has frequently been an incorrect association of Collembola with damage to live plant material. Womersley (1939) recorded both B. hortensis and B. viridescens (as B. arvalis) as injurious in pastures, but provided no further information. In the current study, B. viridescens and B. hortensis hardly fed on subterranean clover cotyledons in culture and both species failed to feed on mature, trifoliate leaves. Furthermore, this study showed B. hortensis is rare in pastures and although B. viridescens is common in Tasmanian pastures during late spring and early summer, with populations recorded up to 6600 $m/^2$ (Chapter 8), there was never any indication of damage in the monitored plots.

Any damage to green plant material by Bourletiella spp. may be mostly confined to the soft tissue of newly emerging field crop seedlings, as observed in culture on oil poppies. The main effect of such depredations in the field being to retard growth rather than cause significant damage (Mason pers. comm.). To the Tasmanian poppy industry Bourletiella spp. are considered an annual risk factor in a small percentage of crops. Based on the high value of the crop compared to the relatively low cost of insecticide it is considered by the industry that the application of

sprays to paddocks, where large numbers of Bourletiella are active, is a justified insurance against damage, even if the possibility of such damage is low, assuming the absence of S. viridis.

Seedling damage by B. hortensis has been widely reported in Europe (Brittain 1924, Davies 1926, Edwards and Heath, 1964), North America (Fink 1914, Folsom 1933, Maynard 1951), Canada (Macnamara 1924, Marshall and Ilyntsky 1976) and Japan (Honma 1988) and together with B. arvalis in New Zealand, it has reportedly damaged seedling crucifers (Cleland 1955). The latter author records instances of complete destruction of seedlings by the Bourletiella spp. if cotyledons were destroyed before the fourth leaves appeared, although once passed this stage they generally survived 'as long as populations and climate factors were not limiting'.

Under field conditions, the severity of damage may depend on the availability of alternative food sources. The culture observations showed that Bourletiella spp. consumed relatively larger amounts of moistened dead and decaying tissue than the tissue of live seedlings. Harding and Stuttard (1974) point out that vegetable substitutes tender from decay or the micro-organisms responsible for tissue breakdown (which may be essential for the feeding of some species) are a preferred collembolan food source. Studies on the gut contents of B. hortensis by Marshall (1978) suggested that the species was an indiscriminate feeder, showing no preference for higher plant material other than a preference by nymphs for pollen grains which are a highly nutrititive food source for species of Bourletiella spp. and other Collembola (Kevan and Kevan 1970). Green plant material in the form of young weed seedlings also offers an alternative food source (Bevan 1965). However, if alternative food supplies are limiting, it is possible that Bourletiella spp. could concentrate their feeding on young crop seedlings, particularly when large populations are present and in greater competition for food resources.

Although Table 9.3 shows variation in frequency of occurrence, all Collembola recorded in Tasmanian field crops were also recorded in local pastures, and often in high numbers (Chapter 8). As previously discussed it is possible that the appearance of some species in crops may often result from the recent ploughing of improved pasture, enabling the species to become prevalent for short periods of time in a less preferred environment. Volunteer migration into the periphery of field crops may also occur from surrounding pastures or grassland from time to time. Although populations of S. viridis often become a problem when oil poppies are sown in fields recently ploughed from pasture (Withecombe 1978) or lucerne, as evidenced during these surveys, there are no records of other species causing damage as a result of this practice in Tasmania.

The observation that Katianna species may feed on the soft green tissues of newly emerged seedlings under laboratory conditions suggests

classification as potential crop pests, however, it is unlikely that they would become significant pests under Tasmanian field conditions. As already discussed, the low activity of K. australis in pitfall traps coupled with the relatively few records of this and other Katianna species from crop surveys indicates that these species prefer their native grassland habitat or improved pastures (Chapter 8).

Womersley (1939) recorded K. australis together with K. ornata and K. obscura as (Parakatianna obscura) as injurious on T. subterraneum and Wallace and Mackerras (1970) also mention K. australis as 'feeding extensively on clover and other legumes'. However, there was no evidence of K. australis feeding on live seedlings or mature leaves of this plant in the culture experiments. In addition, populations of this species estimated at densities up to 5,200/m^2 were identified in L. perenne/T. repens dominant pastures, with no apparent damage to the clover component (Chapter 8). These observations and the relatively higher consumption of decaying plant material in culture suggest that the Katianna species may have been directly feeding on damaged tissue, or grazing on associated fungi after the initial damage was inflicted by another agent. However, if instances of field damage to clover by Katianna species have occurred, the evidence suggests they are a rare occurrence.

Lack of affinity of K. australis for live seedlings of subterranean clover could be due to the plants physical attributes which may have evolved as a protection against the predation of the abundant phytophagous small arthropods of pastures (including species of Bourletiella). The resistance of plants to insect feeding because of a thickened cuticle which hardens as it matures and the presence of prominent leaf hairs making the plant less favourable to attack, was discussed by Southwood (1973).

Compared to oil poppies, the cotyledons of subterranean clover have thick cuticles which would be difficult for small mouthparts to penetrate; leaf hairs could also confer a measure of resistance to small Collembola. The inability of small mouthparts to penetrate certain tissues could also explain the observation that apart from S. viridis, adults of other sminthurids that were tested (being at least about half the size of some adult S. viridis) only attack soft green tissue of plants such as P. somniferum and not the older tissues, which harden with age.

The smaller sminthurids collected in the survey, J. stachi australiensis and Sphaeridia pumilis (adults of both < 1mm in length) are not considered to be green plant feeders. Their activities are confined to the humus and litter layers probably feeding mainly on fungi as does S. elegans (Greenslade and Greenslade 1983), the latter two species being more common in pastures.

The less common D. sulphureus mediterraneus occurs mainly on introduced

grasses and clover during late spring and summer where pollen is a possible primary food source (Kevan and Kevan 1970).

Three other species also not regarded as being of any significance as primary feeders of green plant tissue are the isotomids C. thermophilus and I. tigrina and the neanurid, B. platensis. All are mainly humus and litter inhabitants, litter probably providing a high proposition of the diet of the former two species whereas the abundant B. platensis (which lacks mandibles) feeds through a water film, possibly on fungal spores, bacteria and other micro-organisms (Greenslade and Greenslade op. cit.).

The remaining species H. manubrialis, H. vernalis, H. denticulata, I. palustris, E. sp. cf. lanuginosa E. multifasciata, E. marginata and E. unostrigata have all appeared on lists of injurious Collembola presented by Collinge (1909), Theobald (1911), Mills (1930), Folsom (1933) and Womersley (1939) and Paclt (1956). Further discussion of the pest status of Hypogostrura spp. is given in Chapter 12 and although several of these are listed as injurious to the roots and seedlings of a variety of plants on all the abovementioned lists, there is little information given to substantiate claims of primary damage. Again, the injury to plants caused by a number of species on these earlier lists may have been a reference to secondary feeding following damage by a primary agent, as was probably the injury by Katianna spp. recorded by Womersley (1939).

Overseas, field damage by I. palustris to tobacco seedlings was reported by Splendore (1912) (cited by Paclt (1956)) and to mangolds by Davies (1925). The latter author also reported observing the species feeding on mangold seedlings in the laboratory. However, consideration of the widespread occurrence of I. palustris in the Tasmanian culture steppe, the lack of association with primary damage during surveys, the ready consumption of dead plant material (Fig. 9.36) and the low levels of damage on live plants inflicted by this species in culture (cucumbers being the only species attacked) suggests that the healthy tissues of live plants are not generally favoured as a food source, so that any reports of damage should always warrant an assessment of the circumstances involved.

The 4 entomobryids have yet to be implicated in causing primary damage to plants in Tasmania. All species occur on cultivated ground amongst the litter layer or at the soil surface and probably favour dead plant material, fungi or pollen as a food source. The fact that populations of these species tend towards summer maxima (Chapter 8) further diminishes their pest potential in local crops. However, the observation that E. unostrigata (the cotton springtail) fed on the green tissue of cotton (Gossypium sp.) and on no other plant species tested, again demonstrates variation in susceptibility of plant species to collembolan damage. The susceptibility of cotton to damage by E. unostrigata agrees with the results of Owen and Owen (1958) who were able to reproduce damage on

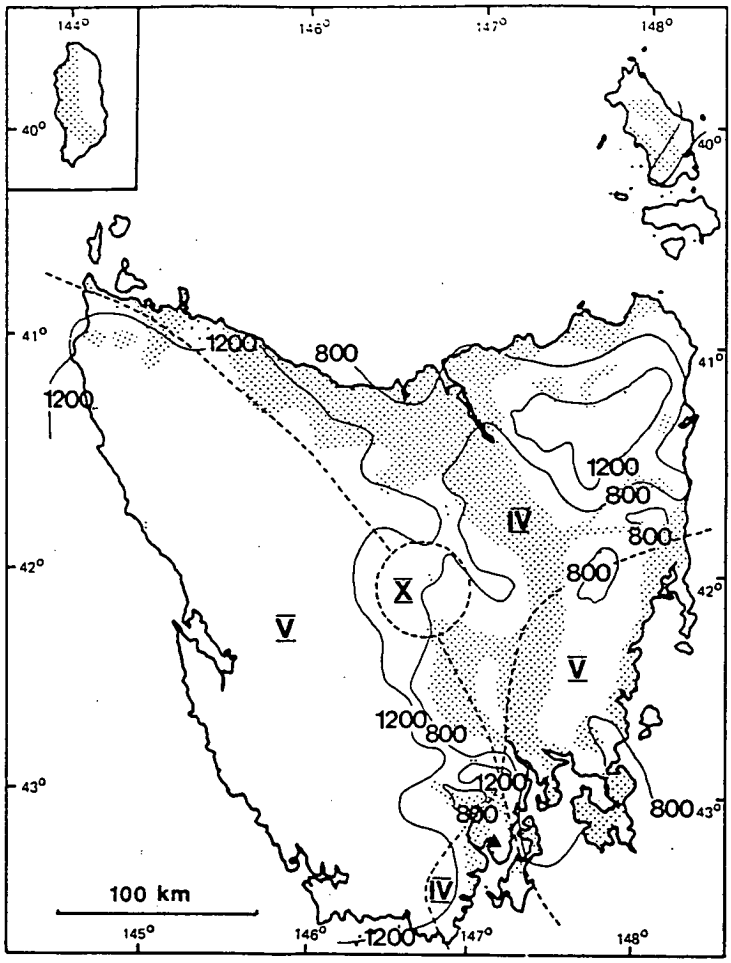
cotton seedlings in culture similar to that observed in the field. Additionally, damage to young seedlings of tomatoes, lettuce and onions by E. unostrigata in the Salinas Valley of California is reported by Scott (1964).

Obviously, factors that either predispose plants to attack by some species of Collembola or stimulate some species of Collembola to attack certain plants needs further investigation. Collembola may be attracted by organic compounds produced by plants suffering from nutritional or water stress (Kennedy et al 1958; Graham 1983) and there is evidence that certain compounds produced by plants such as sugars and alcohols may stimulate feeding (MacNamara 1924; Greenslade and Greenslade 1971).

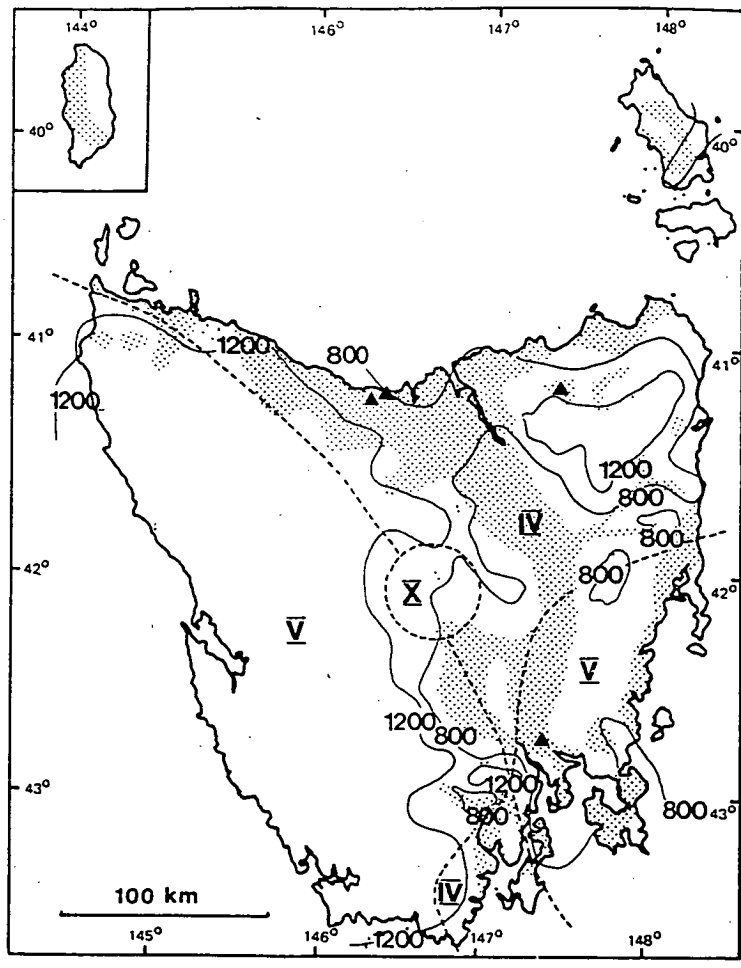
Bruzzese (1980) recorded 4 collembolan species (E. sp. cf. lanuginosa, Setanodosa quinseta Salmon, Polykatianna aurea Womersley and Katianna sp.) as feeding on the leaves of blackberries. However, it is more likely they were feeding on dead tissues or grazing on microoganisms. Field observations associating Collembola with primary damage should be confirmed by culture studies if the species involved has not been previously recorded as damaging. Although culture studies indicate whether the species can feed on the particular plant, care must also be taken in extrapolating results to a field situation where there are alternative foods.

Southwood (1973) points out that most Collembola are associated with soil and litter and normally feed on material such as decaying plants and associated microorganisms that are abundant in these niches. Although species other than S. viridis (such as B. hortensis) occassionally assume pest status, Collembola as a group have not quite evolved the ability to fully exploit seed plants.

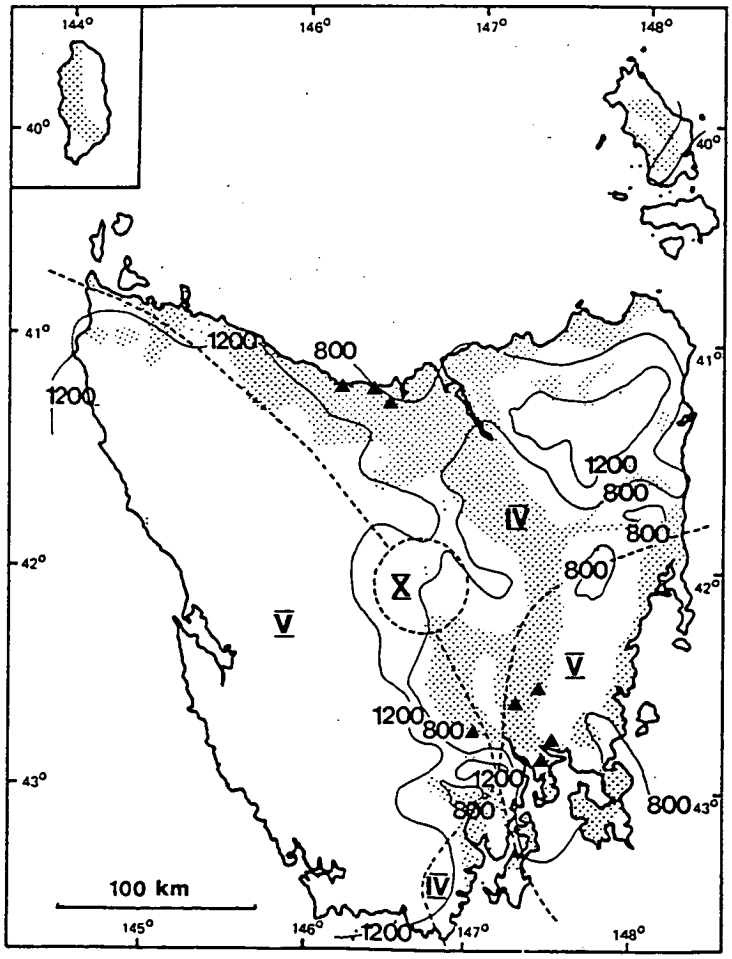
Figs 9.4-9.29 Collection sites for individual surface-active collembolan species in Tasmanian field crops in relation to the climatic zones of Walter and Lieth (1967) and the 800 and 1200 mm annual isohyets (stippling on each map is equivalent to the approximate area of sown pasture, ca 900,000 ha).



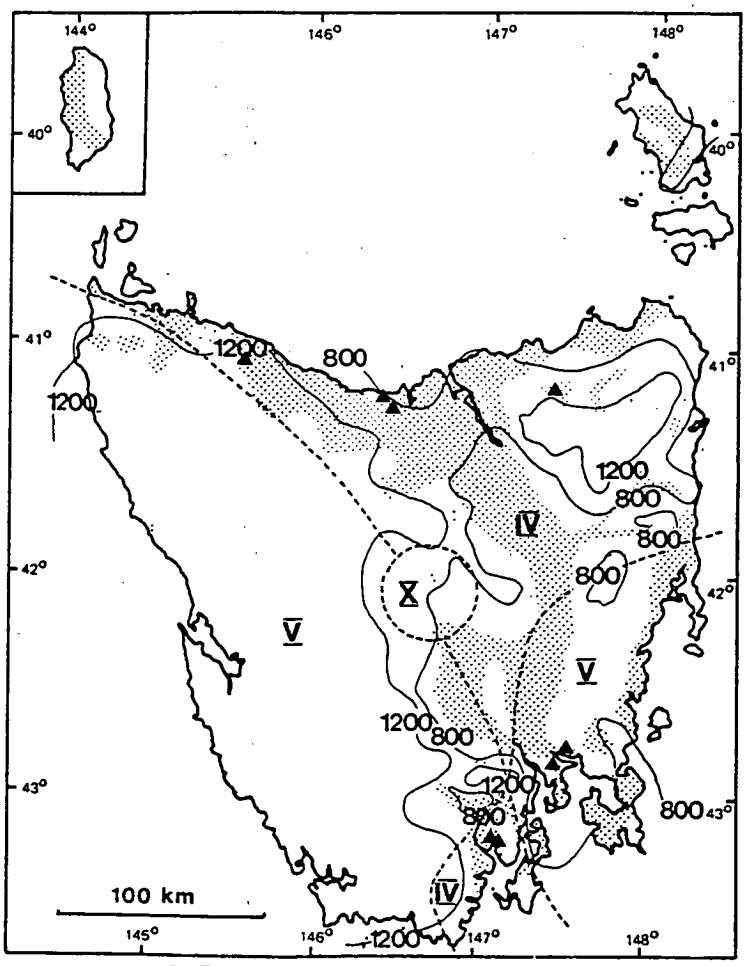
9.4. cf. *Dicyrtomina* sp. 1



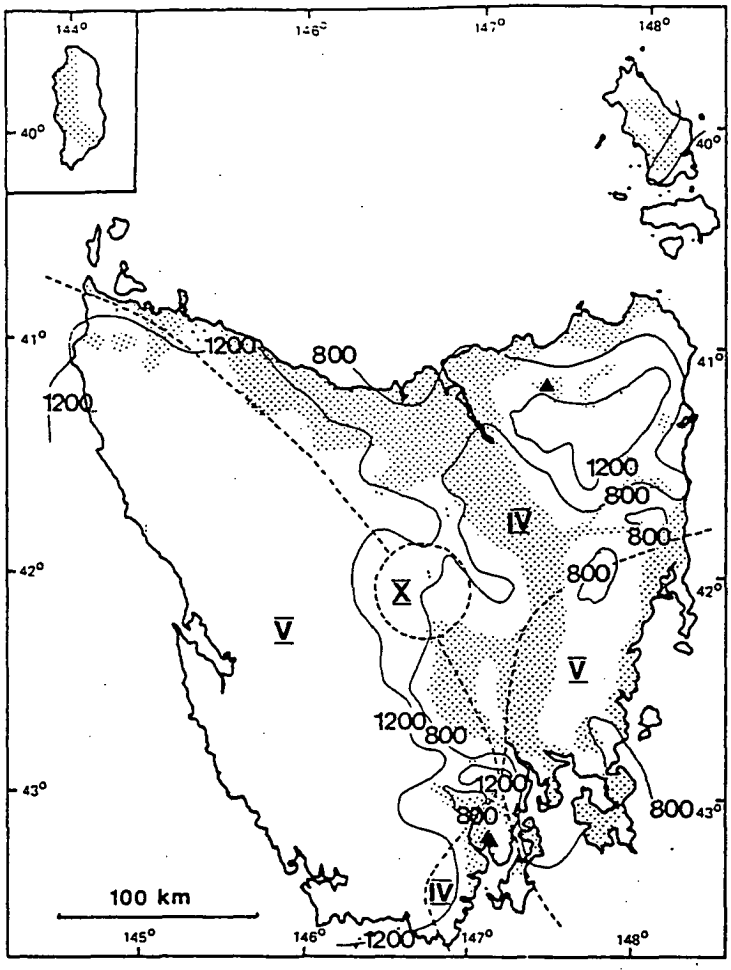
9.5. *S. pumilis*



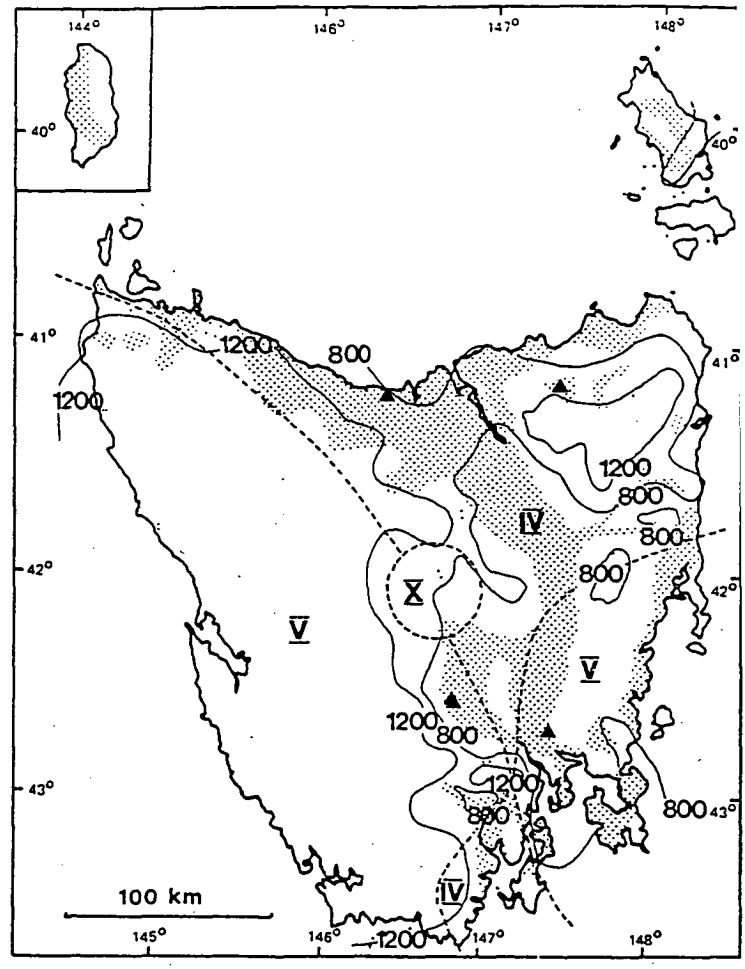
9.6. *J. stachi australiensis*



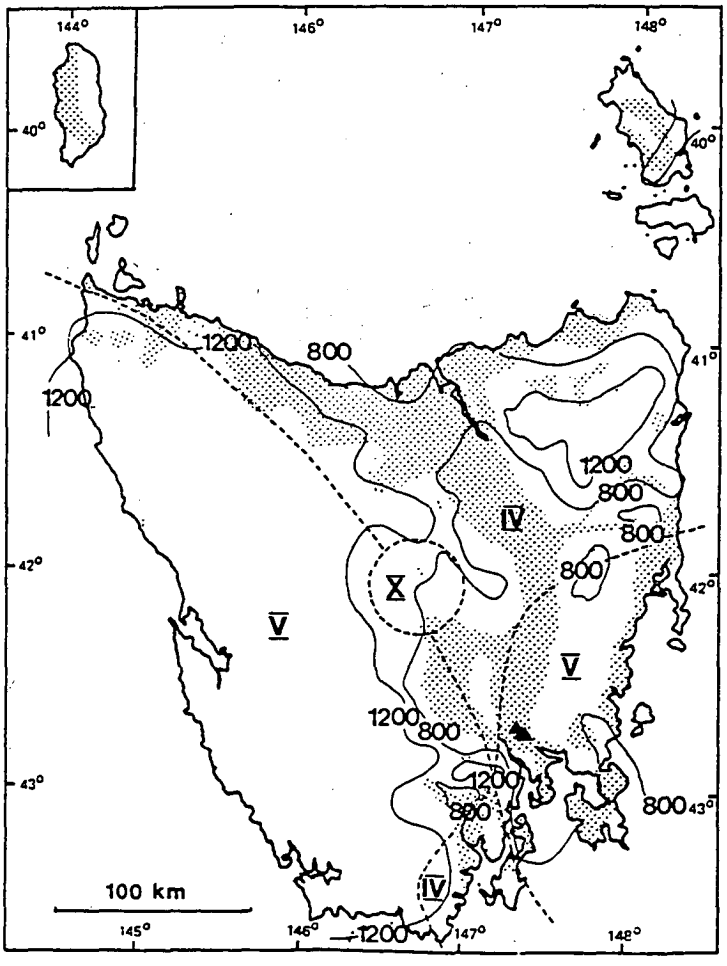
9.7. *K. australis*



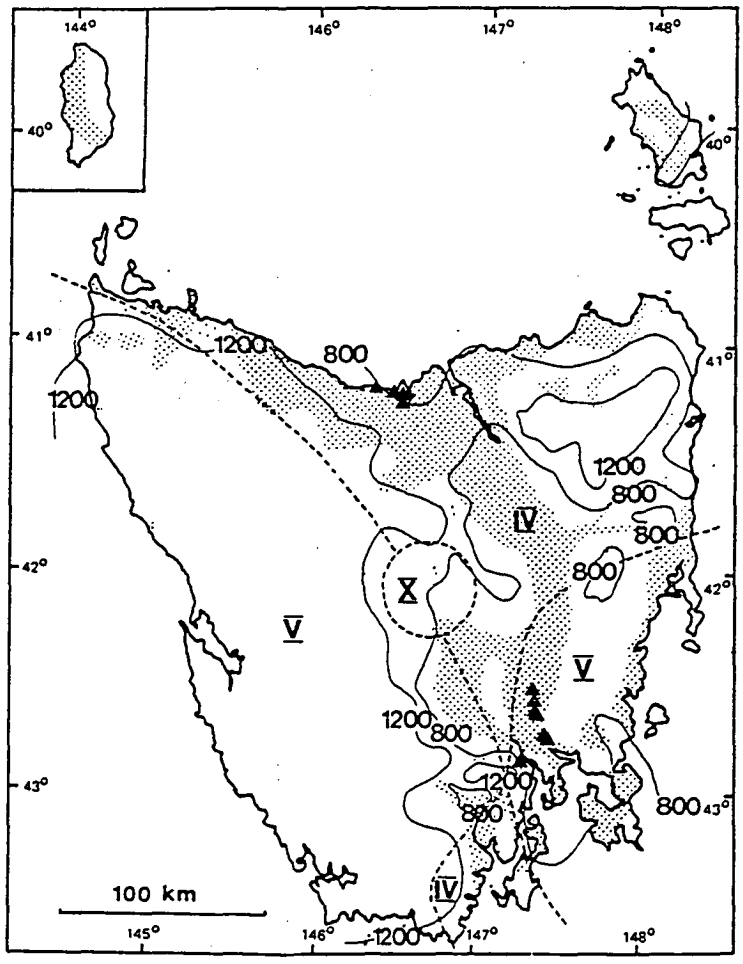
9.8. *K. oceanica* var. *schoetti*



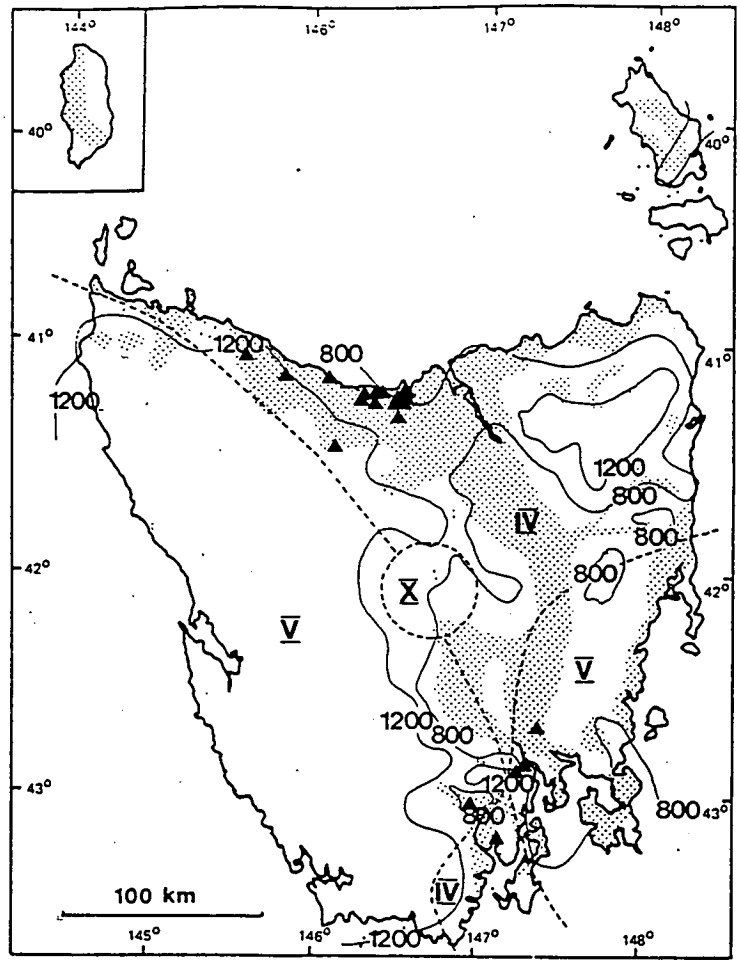
9.9. *S. elegans*



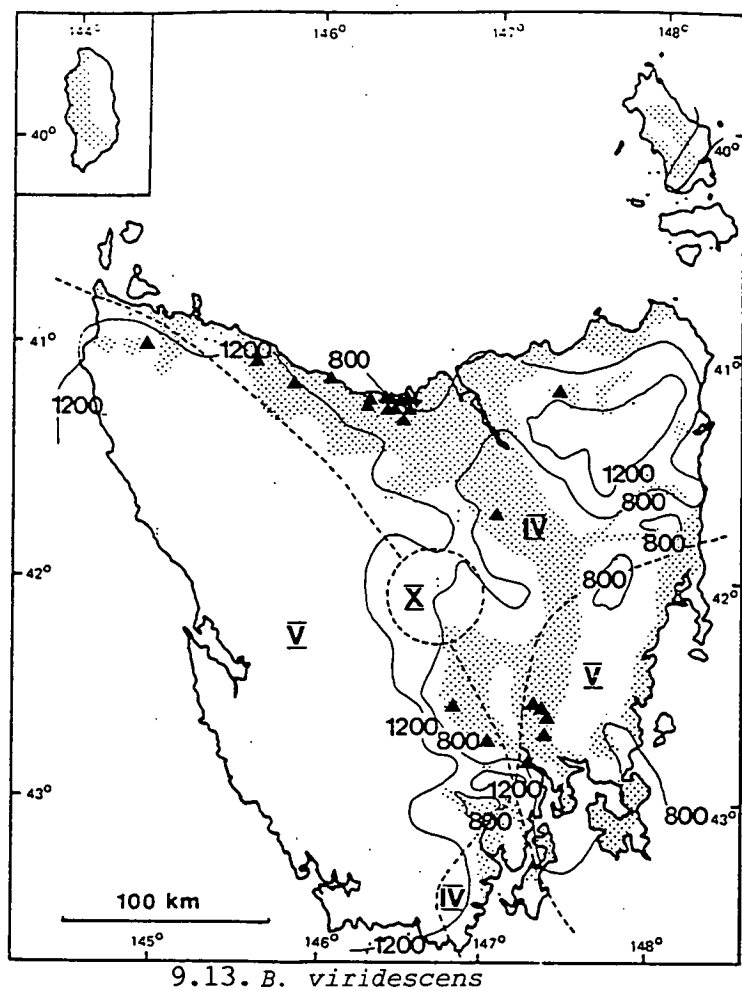
9.10. *D. sulphureus mediterraneus*



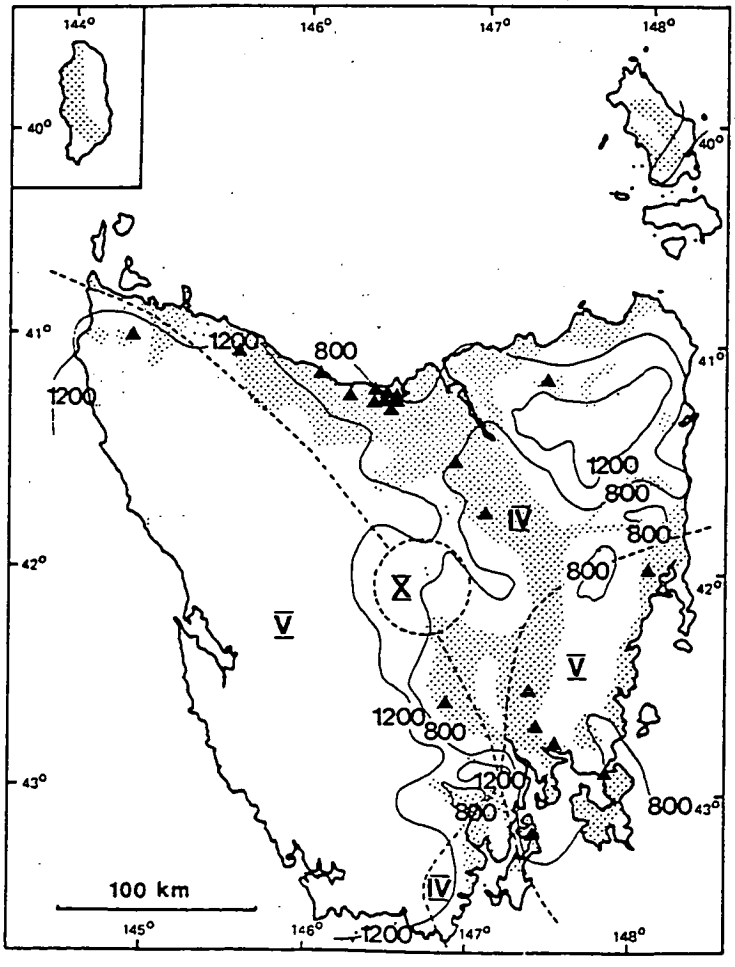
9.11. *P. quinquefasciatus*



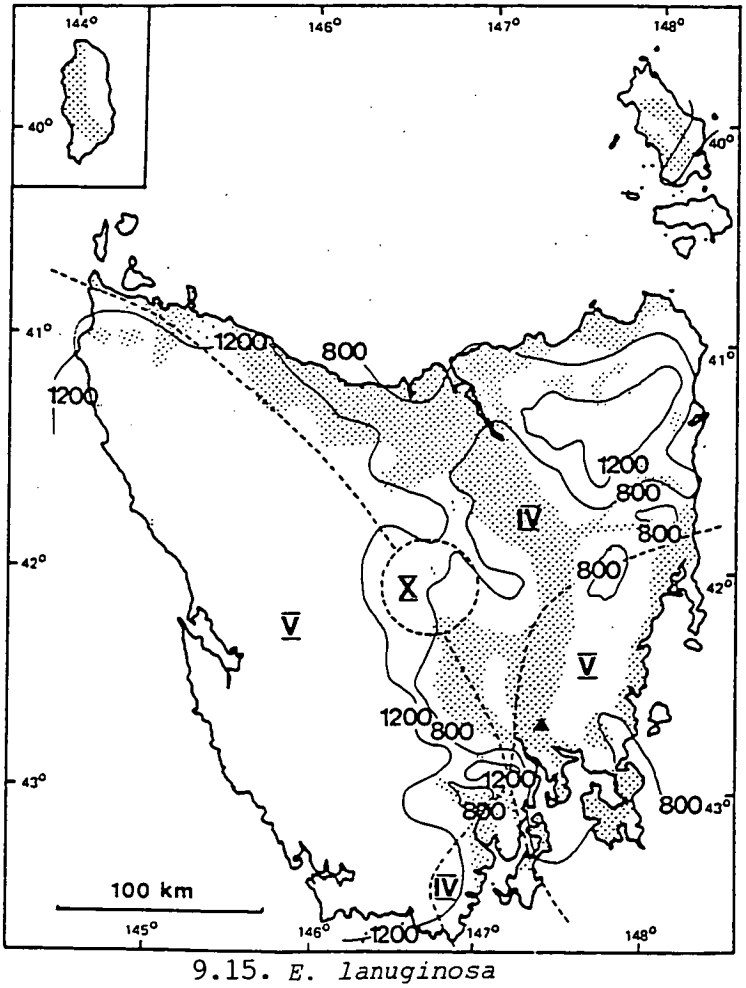
9.12. *B. hortensis*



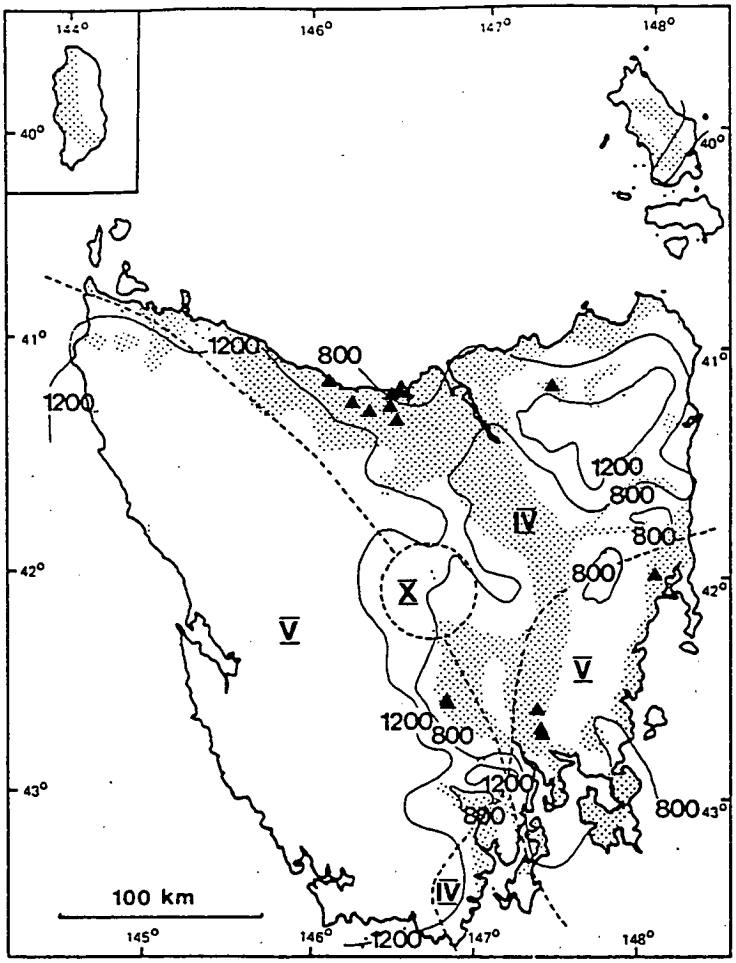
9.13. *B. viridescens*



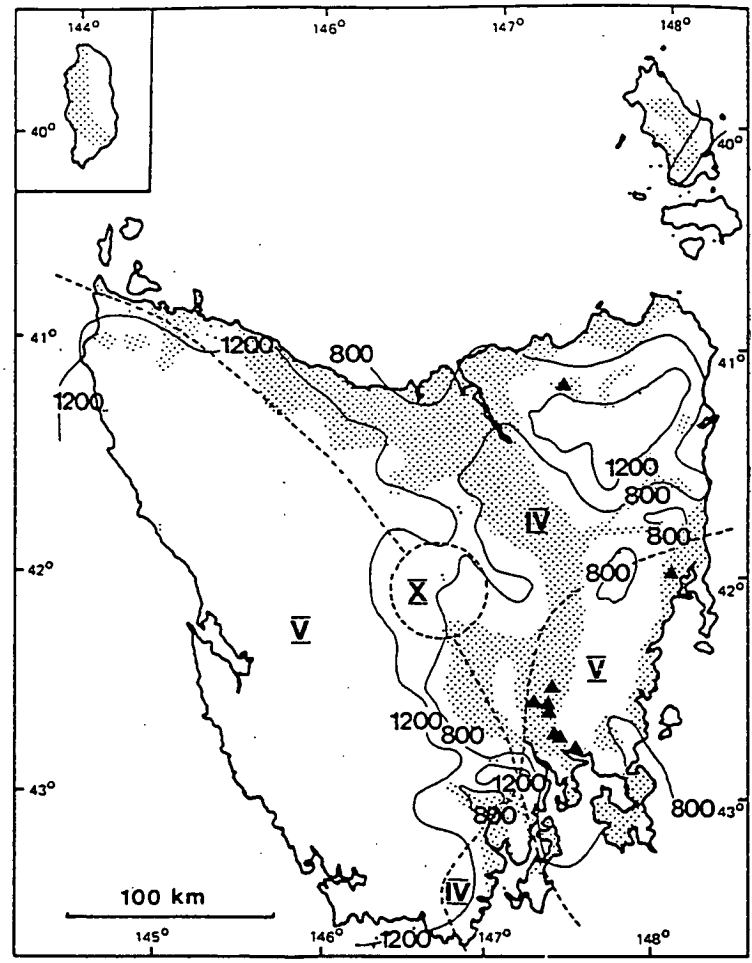
9.14. *S. viridis*



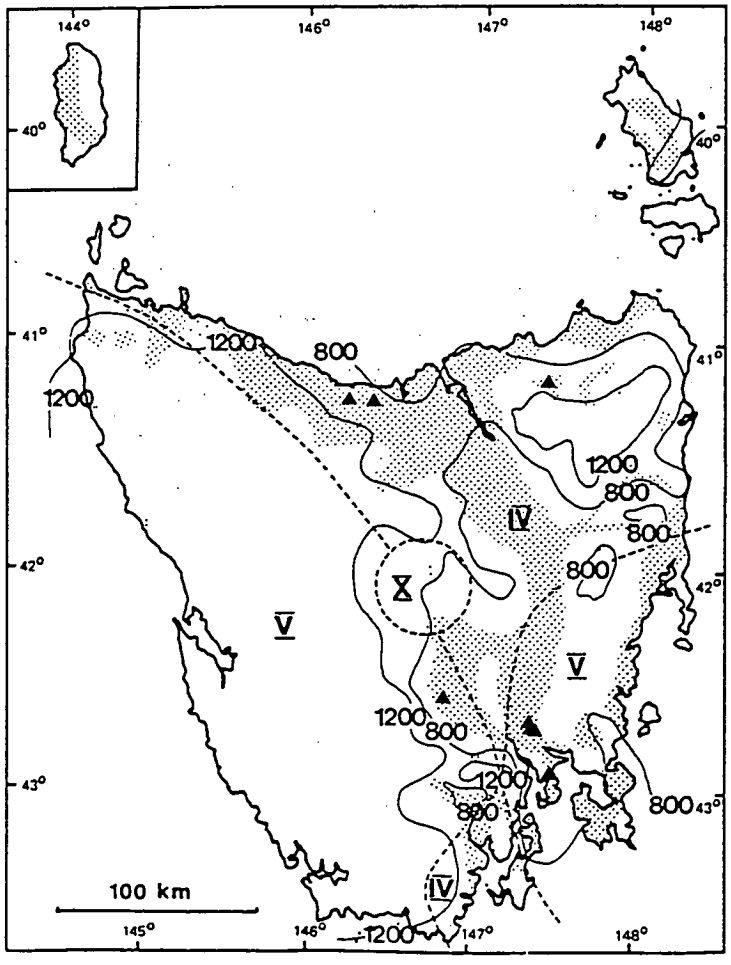
9.15. *E. lanuginosa*



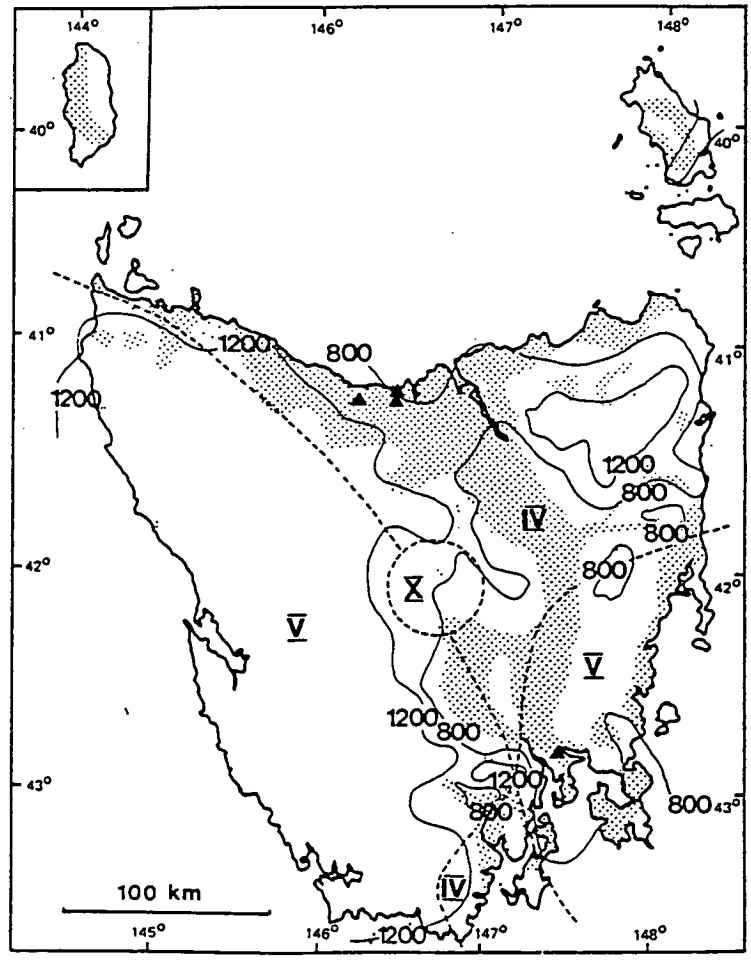
9.16. *E. marginata*



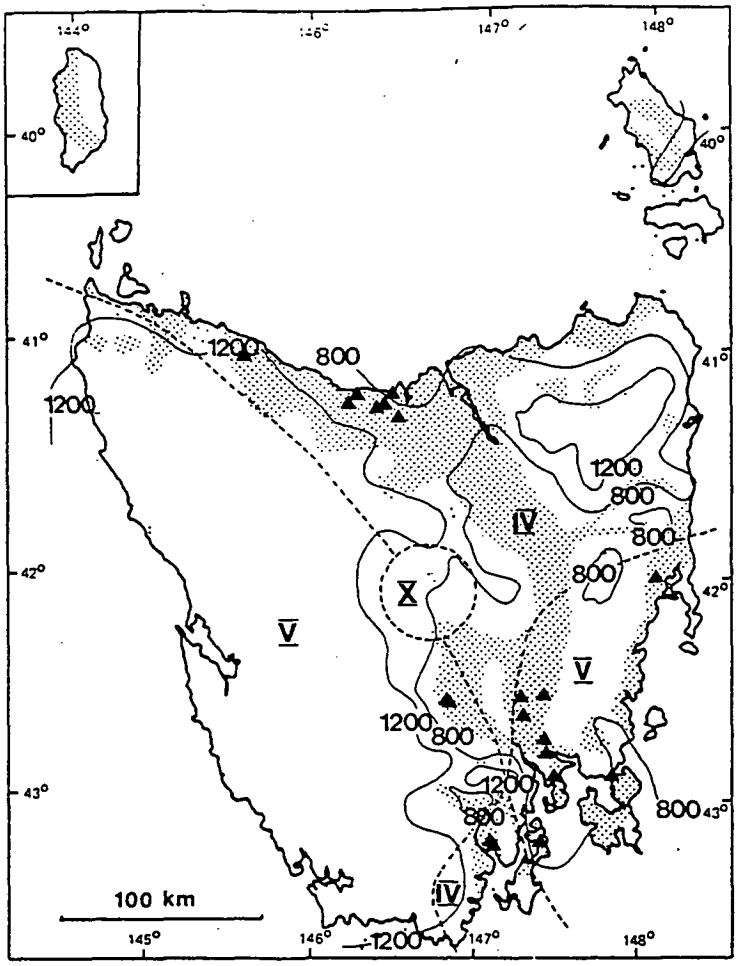
9.17. *E. multifasciata*



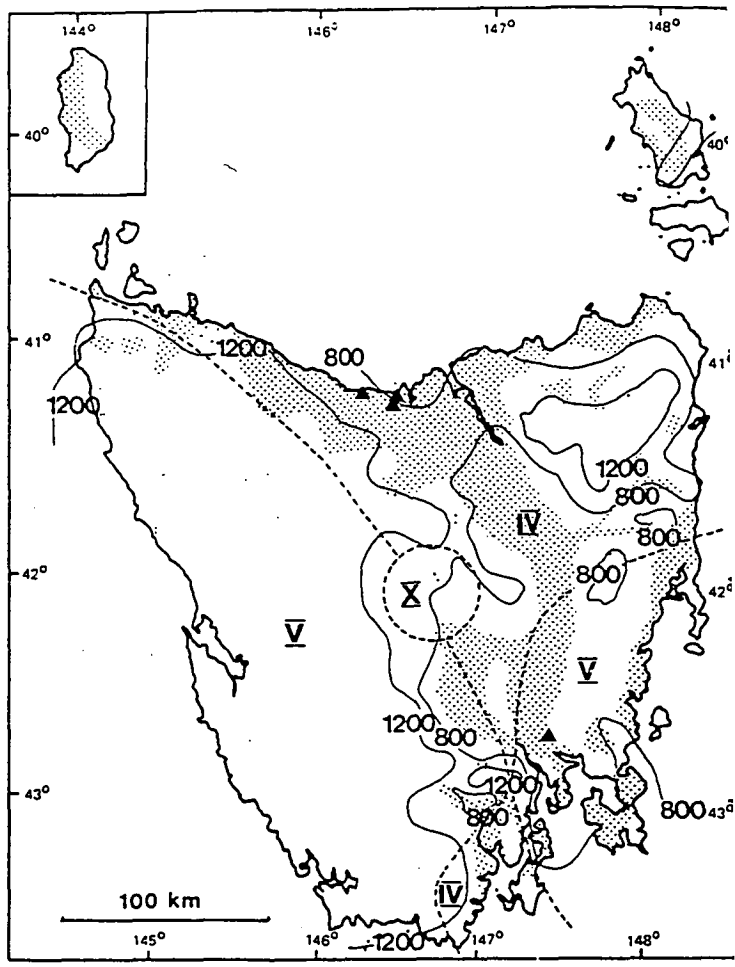
9.18. *E. unostrigata*



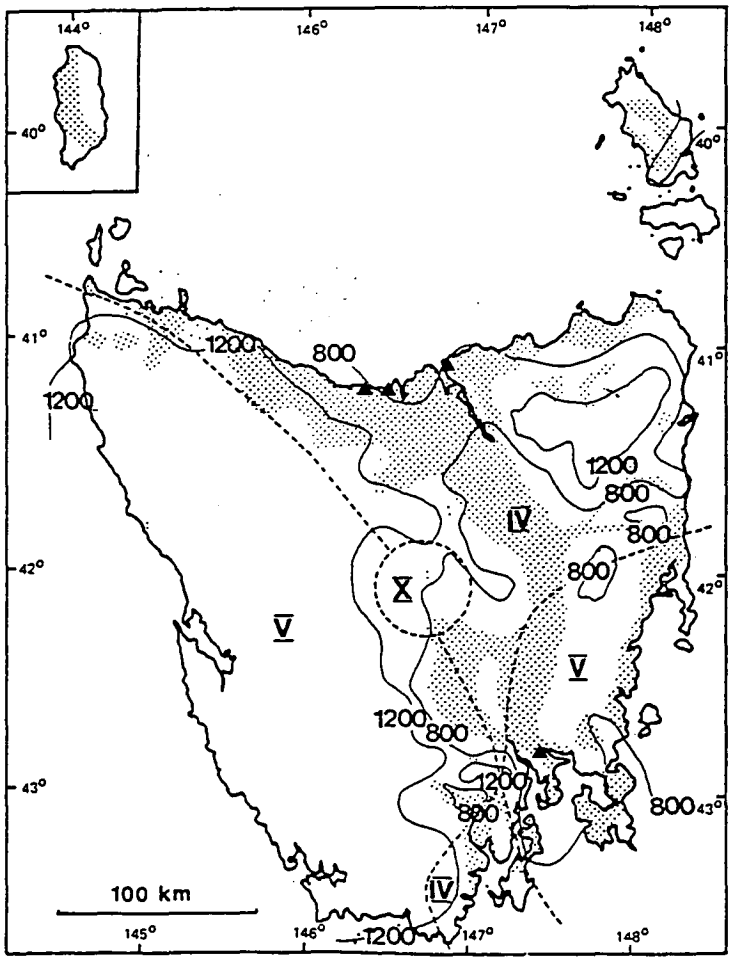
9.19. *C. thermophilus*



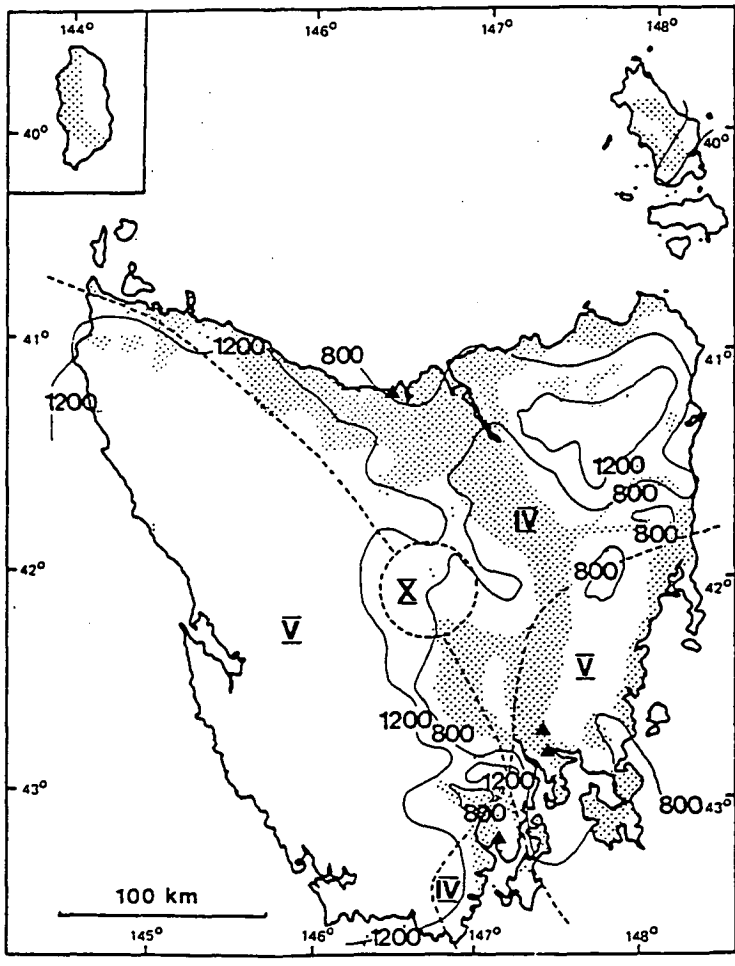
9.20. *I. palustris*



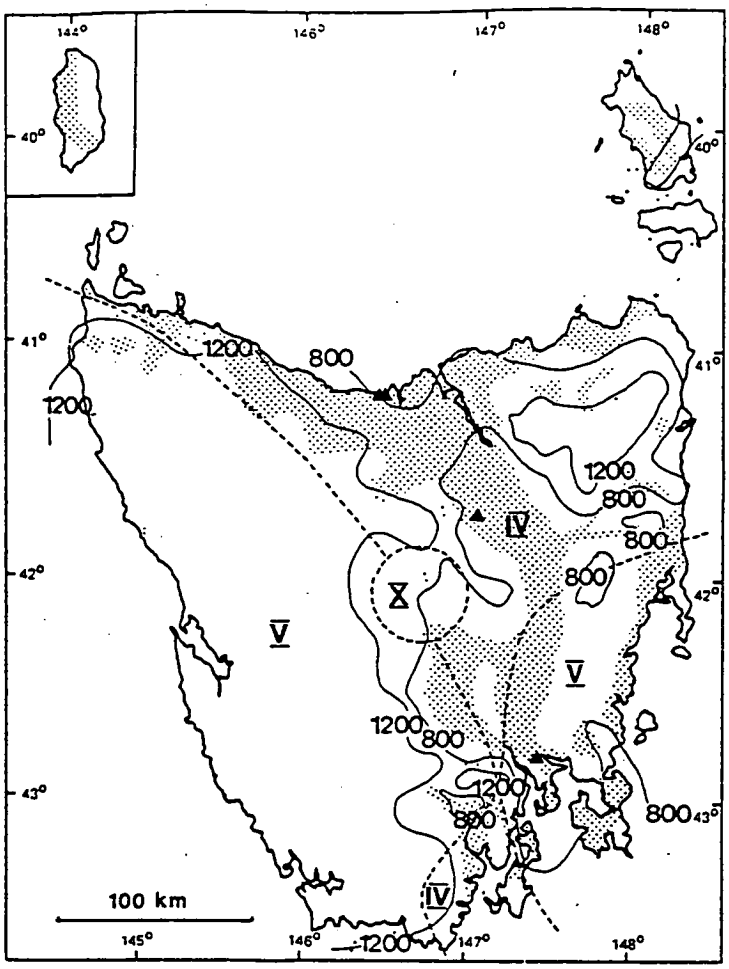
9.21. *I. tigrina*



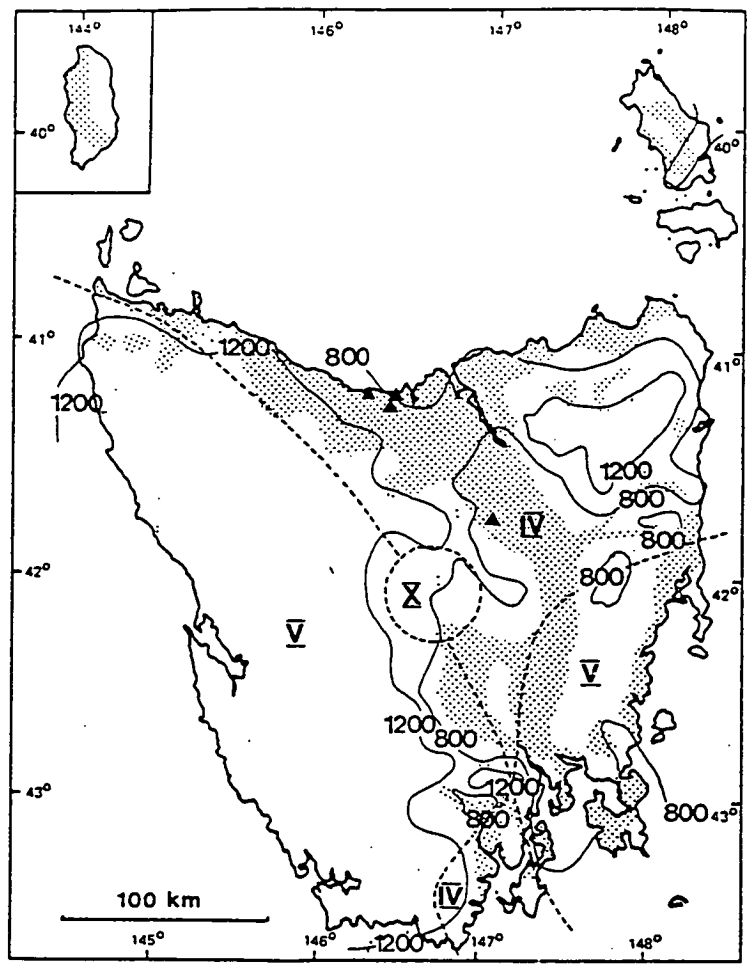
9.22. *H. denticulata*



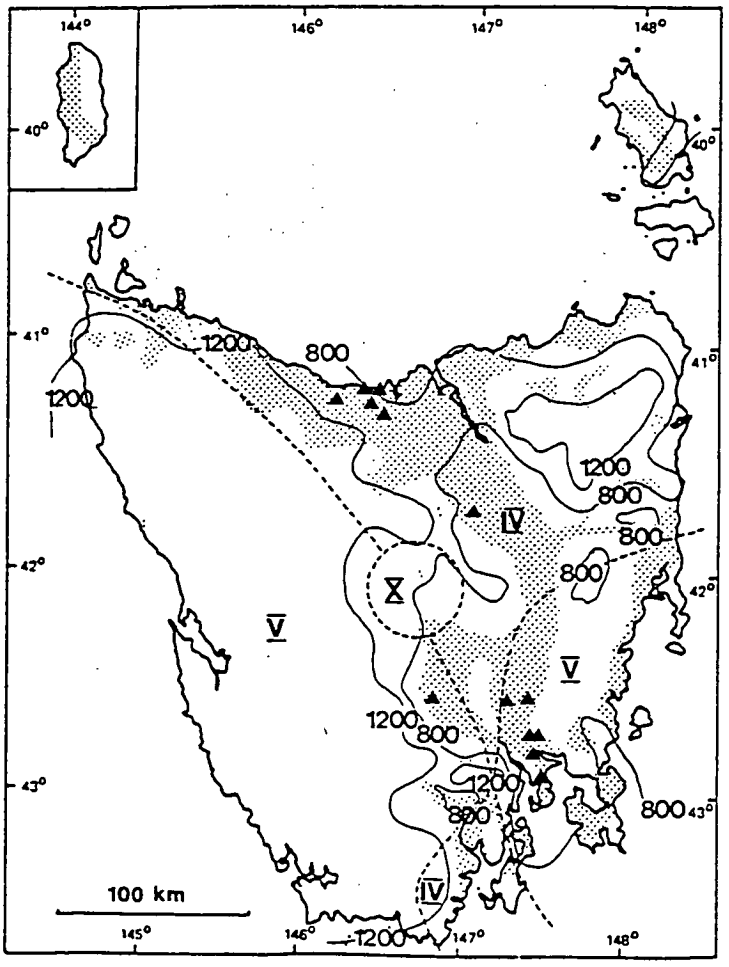
9.23. *H.* sp. cf. *engadinensis*



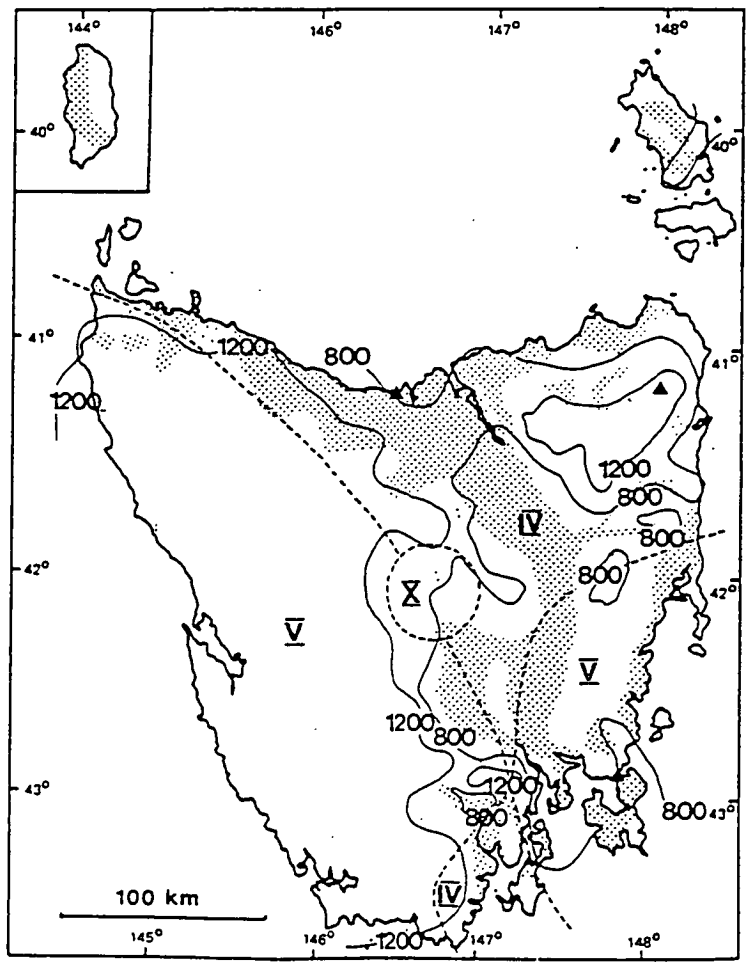
9.24. *H. gibbosa*



9.25. *H. manubrialis*



9.26. *H. vernalis*



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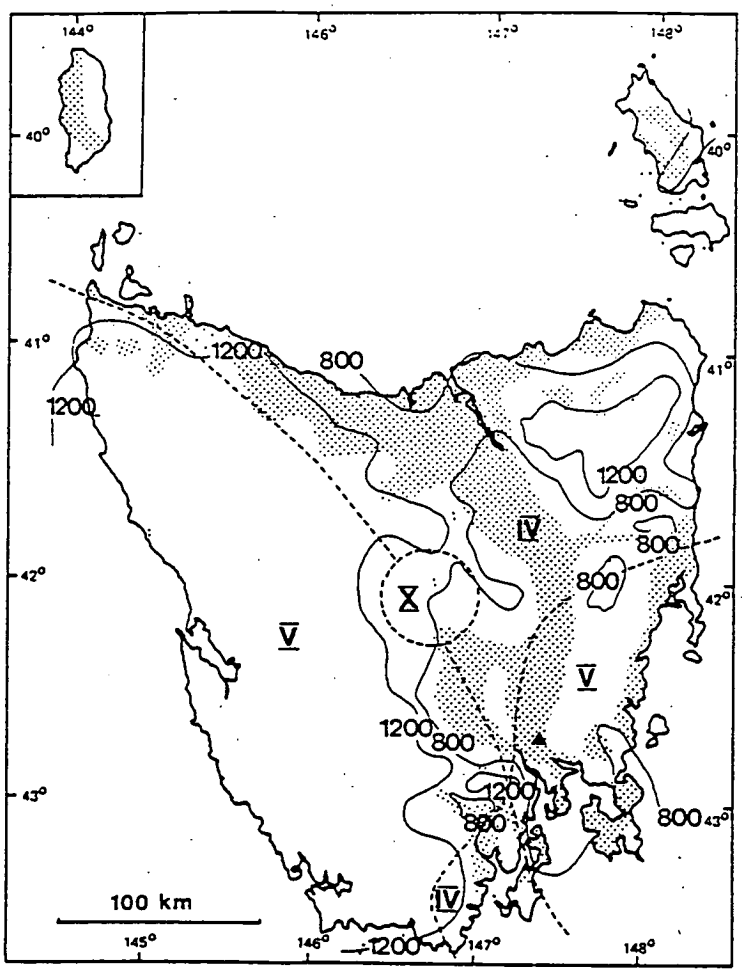
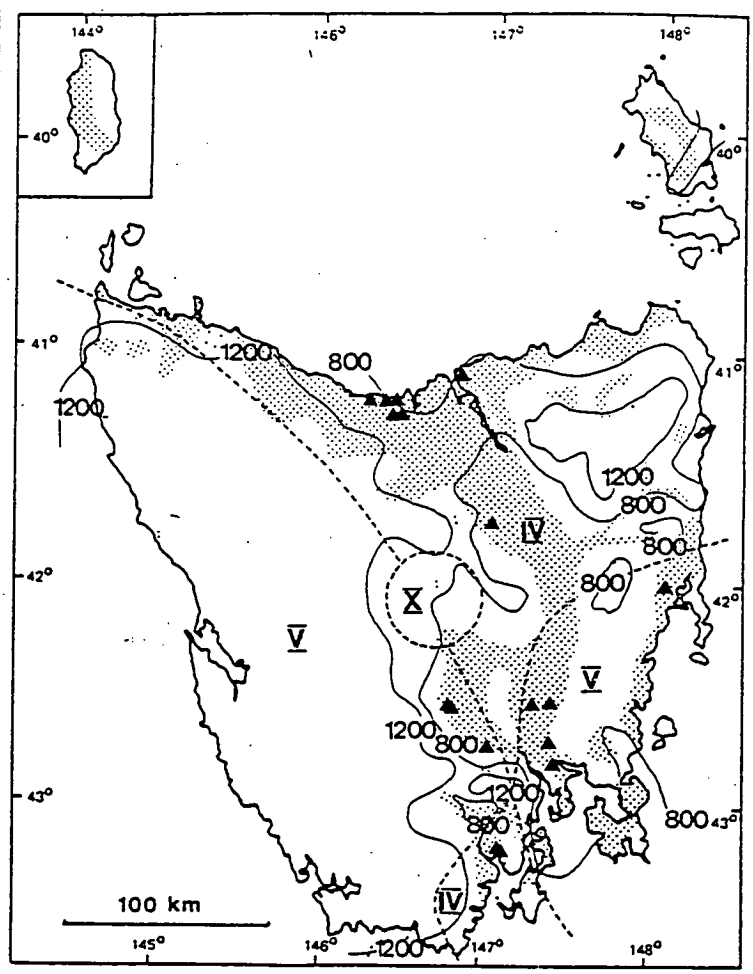


9.28. *Xenylla* sp. 1



9.29. *B. platensis*

Figs 9.30-9.32 S. viridis damage to oil poppy (Papaver somniferum): (30) leaf damage (field); (31) feeding on seedlings in culture; (32) cotyledon damage (culture).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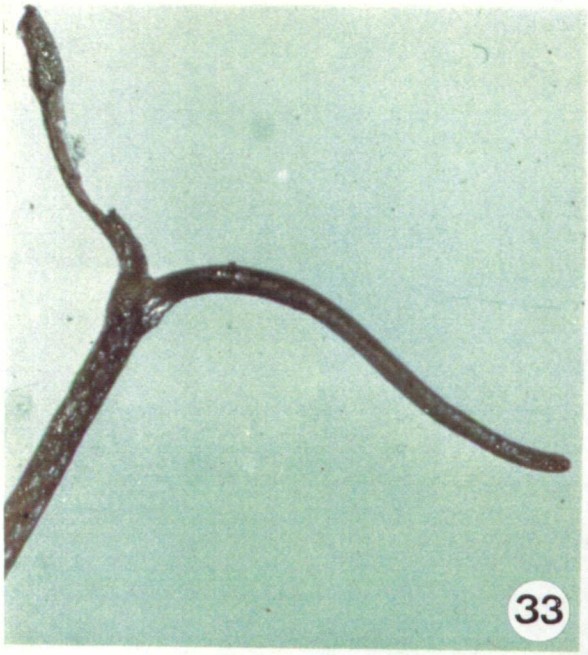
Figs 9.33-9.38 (33) K. australis damage to cotyledons of oil poppy (Papaver somniferum) (culture); (34) B. hortensis damage to cotyledons of cucumber (culture); (35) I. palustris damage to cotyledons of cucumber (culture); (36) remains of decaying oil poppy grazed by I. palustris (culture) (note live positions of tissue untouched); (37-38) E. unostrigata damage to cotyledons of cotton (Gossypium sp.) (culture).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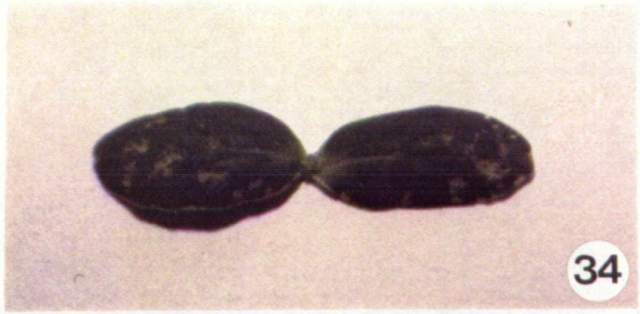
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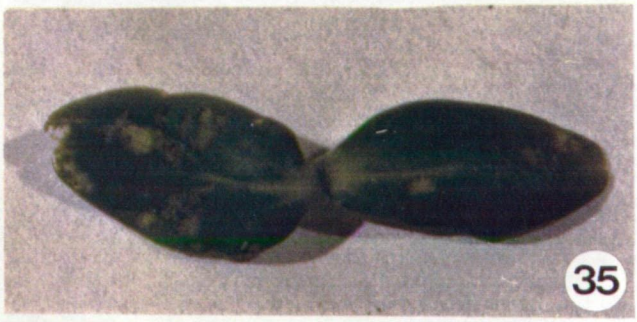
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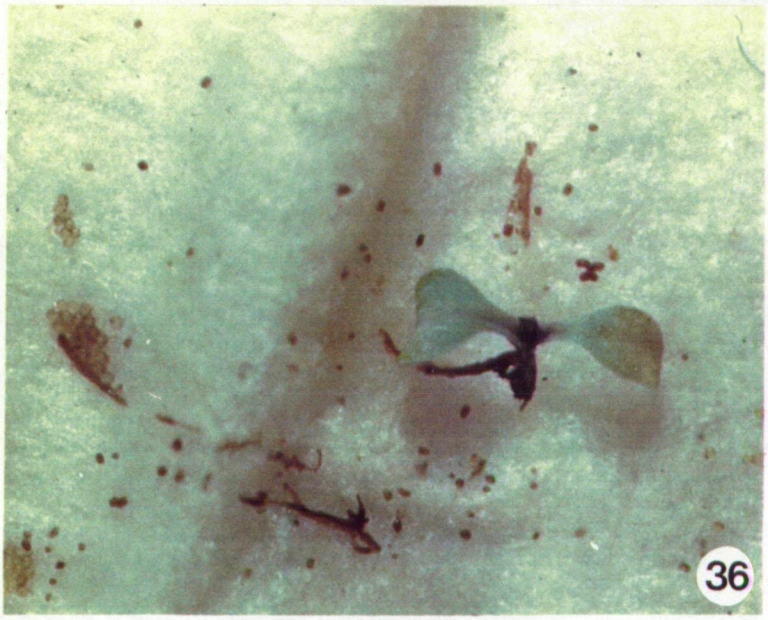
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CHAPTER 10

IDENTIFICATION AND PEST STATUS OF SOME EUEDAPHIC COLLEMBOLA IN THE TASMANIAN CULTURE STEPPE, WITH PARTICULAR REFERENCE TO THOSE ASSOCIATED WITH ROOT DAMAGE

INTRODUCTION

Some species of euedaphic springtails are of particular interest because of their long association with damage to the roots of a variety of plants. Lists of supposedly injurious Collembola in the northern hemisphere by Collinge (1909), Theobald (1911), Mills (1930), Folsom (1933) and Paclt (1956) all include species of Onychiurus (or its synonyms). Other euedaphics belonging to the genus Folsomia are also recorded as damaging (Paclt op. cit.). Particular instances of damage attributed to Onychiurus spp. have been recorded in Louisiana, USA, where O. armatus was recorded by Spencer and Stracener (1929) as damaging sugarcane roots, in the Salinas Valley, California where O. armatus was recorded by Scott (1964) as damaging to seeds and young seedlings of lettuce, celery, broccoli, cauliflower, sugar beet, spinach, lima beans and several species of ornamentals and turf grass, and in western Washington where O. pseudarmatus frequently damages spinach grown for seed (Getzin 1985). In Europe, Onychiurus spp. have been shown to damage the roots of tomato and bean seedlings (Brown 1954; Edwards 1962) and are now regarded as pests of sugar beet and have become the subject of much research (Winner and Schäufele 1967; Heijbroek 1971; Baker and Dunning 1975; Joosse and Koelman 1979; Grégoire-Wibo 1980; Heijbroek et al. 1980; Brown 1983, 1984, 1985). In Australia, Womersley (1939) also recorded species of Onychiurus and Folsomia from mainland States as being injurious to plant roots, although his attributions of damage were probably based on the data from overseas publications. In Tasmania, investigations into the pest status of S. viridis and other surface-active Collembola for this current study were extended to include some euedaphic species because of the number of reported instances of plant damage with which they were associated, usually in home gardens. Some work was also done on the identification of the species involved. The taxonomy of the genus Onychiurus is complex and no group of Collembola has been subject to more generic fragmentation (Christiansen and Bellinger 1980b). The characters which have been used to distinguish various species by some workers have been regarded as an inherent variable throughout the population of a single species by others. Stach (1954) criticised some divisions, as being due to "significant ecological or local modifications" and Bödvarsson (1959) regarded some forms as "infrasubspecific which should not be submitted to taxonomic treatment". Gisin (1960) recorded 38 species contained within the Onychiurus armatus species group alone and Hale (1964) assessed Gisin's criteria experimentally on 4 species finding them to be valid. Pitkin (1980) investigated the variation in twenty characters in 298 females and 207 males of the O. armatus group from a number of sites in England and Wales, which fell into 4 morphologically distinct groups he recognised as species. Two of the three known sub-families of Onychiuridae (the Onychiurinae and the Tullberginae) are known to occur in Australia. The Onychiurinae is best represented in the northern hemisphere and although all Australian species are introduced, the Tullberginae have elements of the northern and southern hemisphere (Greenslade in press (b)).

This Chapter reports on the results of surveys for euedaphic Collembola associated with root damage in Tasmania and (i) identifies the species or species groups mainly associated with damage, (ii) examines their occurrence in the culture steppe and (iii) discusses their pest status.

MATERIALS AND METHODS

(i) Collection and identification of specimens

Collection methods and specimen handling procedures for identification and mounting were presented in Chapter 2. Material collected during this study was examined using keys by Womersley (1939), Stach (1954), Gisin (1960) and Christiansen and Bellinger (1980b).

The Onychiuridae have white pigmentation and lack ocelli. Characters used to classify species include the presence or absence of anal spines, the shape, arrangement and number of tubercles in the post-antennal organ (PAO), the number and arrangement of pseudoocelli on the head, thoracic and abdominal segments, and the structure of the apical organ of the third antennal segment (Christiansen and Bellinger 1980b).

OBSERVATIONS AND RESULTS

(i) Identification

Table 1 list the species identified in this study. Apart from Folsomia candida Willem and Proisotoma minuta (Tullberg) (Isotomidae) which are cosmopolitan species (Salmon 1964) all other euedaphics identified during this study belonged to the family Onychiuridae. All collections of Onychiurus examined from the Tasmanian culture steppe fell into 3 main groups, the Onychiurus (Protophorura) sp. armatus (Tullberg) group, the Onychiurus (Onychiurus) sp. fimetarius (L.) group and the Onychiurus (O.) ambulans (L.) group, which are keyed in Chapter 13 with 2 other onychiurid genera (Tullbergia and Dinaphorura), both of which contain species that are not clear systematically. Any attempt to define the individual species that may exist within the groups defined for the Tasmanian culture steppe would require a major study and is considered beyond the scope of this thesis. F. candida and P. minuta are also keyed in Chapter 13.

(ii) Occurrence of Onychiuridae, F. candida and P. minuta (Isotomidae) in the Tasmanian culture steppe

Collection data are detailed in Table 10.1 and collection sites are indicated in Figs 10.1-10.7. Only the Onychiurus species and F. candida were associated with damage to plants roots, and although P. minuta was identified in one instance from daffodil bulbs there was no evidence of primary damage.

The single instances when Tullbergia and Dinaphorura were identified did not involve any association with root damage.

Examination of Table 10.1 shows that the O. armatus group was the most frequently identified. The O. fimetarius group was also relatively

common, often occurring in samples with O. armatus. O. ambulans was uncommon and found only in urban situations as was F. candida. As the data presented in Table 10.1 mainly involves collections made during instances of plant damage, species of Tullbergia, Dinaphorura and P. minuta are probably more common in the Tasmanian culture steppe than records suggest. Berlese extracts of litter from native forests have often revealed species of Tullbergia (Ireson unpubl. data), however these may be native species. Species of Tullbergia (and Dinaphorura) found in the culture steppe are more likely to be introduced.

Table 10.1 Records of occurrence of Onychiuridae and F. candida (Isotomidae) in the Tasmanian culture steppe.

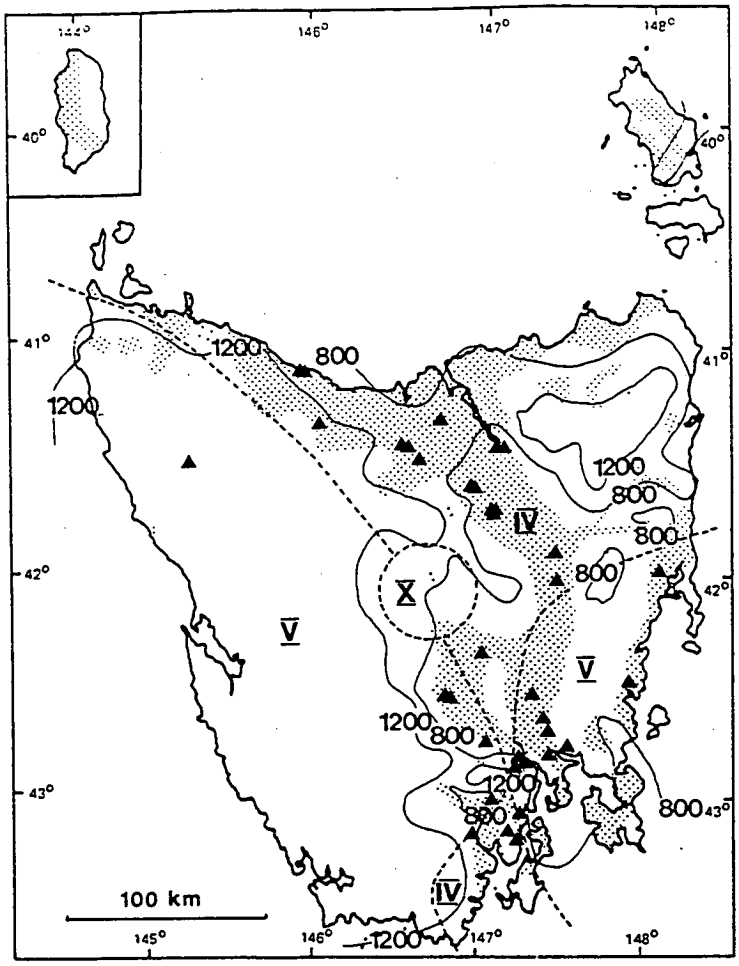
	Pasture	Field crops	Home gardens	Indoor plants	Total records
O. armatus	17	12	22	3	54
O. fimetarius	14	4	11	0	29
O. ambulans	0	0	3	2	4
Tullbergia sp.	1	0	0	0	1
Dinaphorura sp.	0	1	0	0	1
F. candida	0	0	6	4	10
P. minuta	0	0	1	0	1

Instances of root damage to home gardens and indoor Onychiurus makes up ca 46% of their total records and include reports of damage to peas, beans, onions, lentils, maize and wheat as well as chrysanthemum, iris and daffodils. Damage attributed to Onychiurus by home gardeners was usually associated with poor seed bed preparation and invariably reported as poor germination or damage to seedling plants being grown in acid soils with a high organic matter content. F. candida was associated with damage to home garden or indoor plants grown in soil under similar conditions. Of the 10 records of this species the 6 from home gardens were associated with damage to gladioli bulbs (2 records), daffodil bulbs (2 records) and potato tubers (2 records). In these instances damage caused by F. candida seemed to have occurred following mechanical injury to tubers or as a result of stress due to poor cultural practices. The 4 instances of damage to indoor plants were attributed to populations of F. candida being responsible for poor root growth.

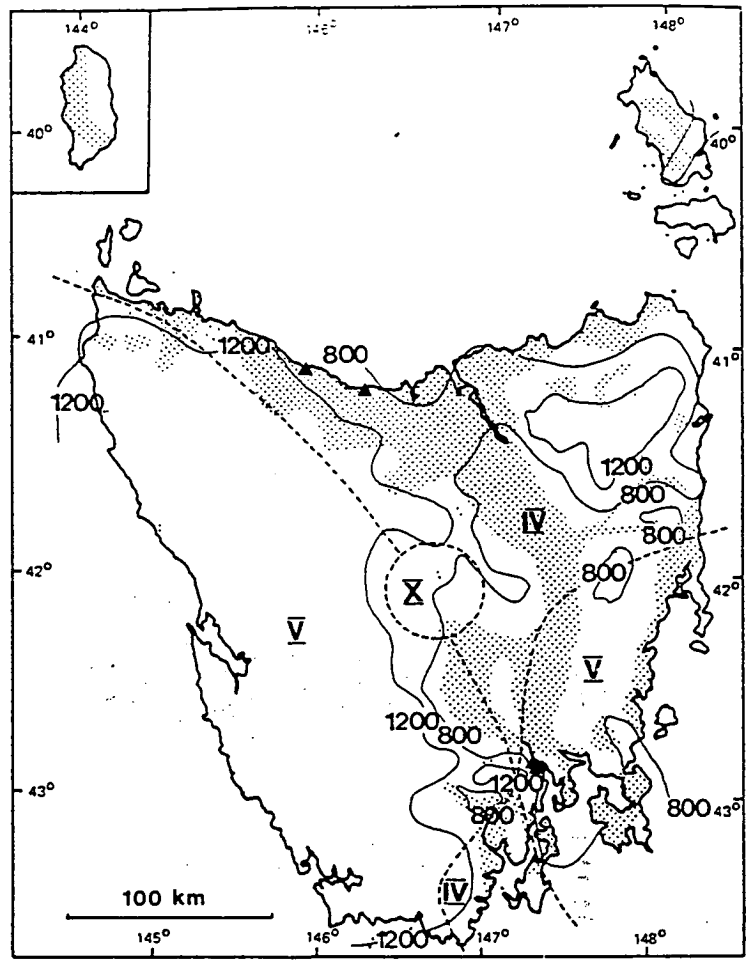
Collection data indicate that Onychiurus species are common in soil particularly in agricultural areas, however, until 1982 there were no reports of species being associated with major damage to field crops in Tasmania.

(iii) Association of damage by Onychiurus to field peas, Cressy, 1982
Between September and October 1982 a number of pea crops sown in the

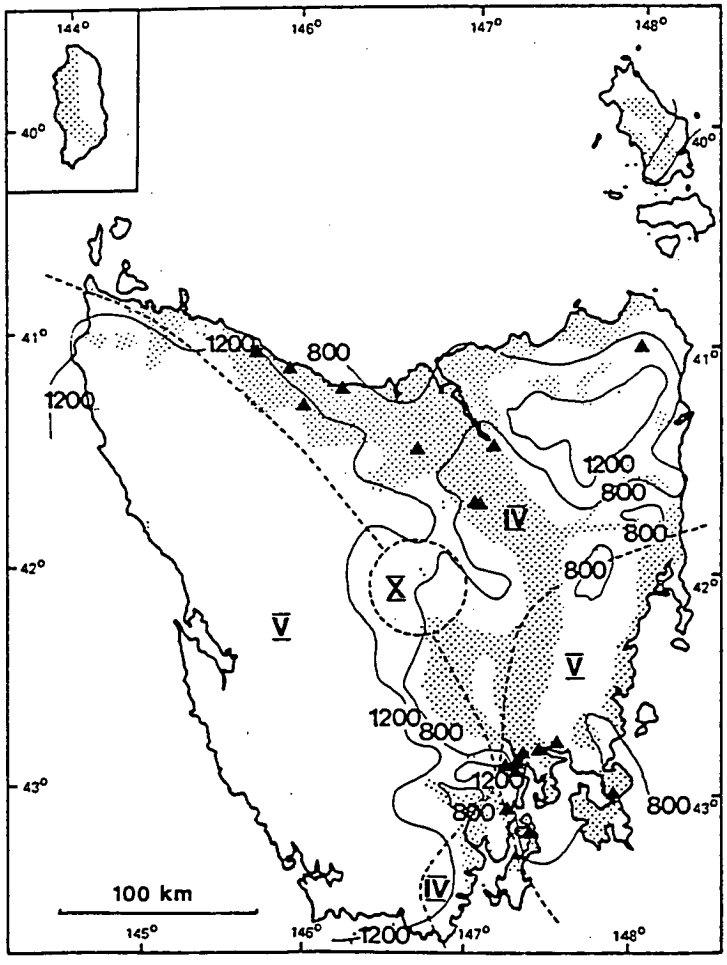
Figs 10.1-10.7 Collection sites for euedaphic Collembola in the Tasmanian culture steppe : (1) Onychurus sp. armatus gp.; (2) Onychiurus sp. ambulans gp.; (3) Onychiurus sp. fimetarius gp.; (4) Tullbergia sp.; (5) Dinaphorura sp.; (6) Folsomia candida; (7) Proisotoma minuta. Sites are shown in relation to the climatic zones of Walter and Lieth (1967) and the 800 and 1200 mm annual isohytes (stippling on each map is equivalent to the approximate area of sown pasture ca 900,000 ha).



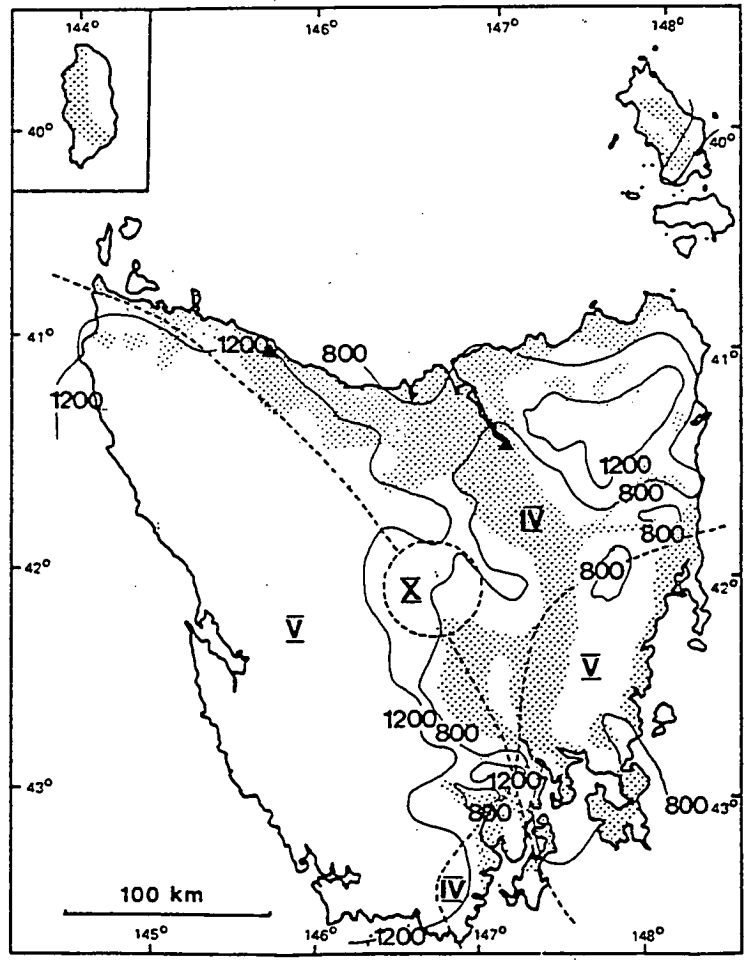
10.1. *O.* sp. *armatus* gp.



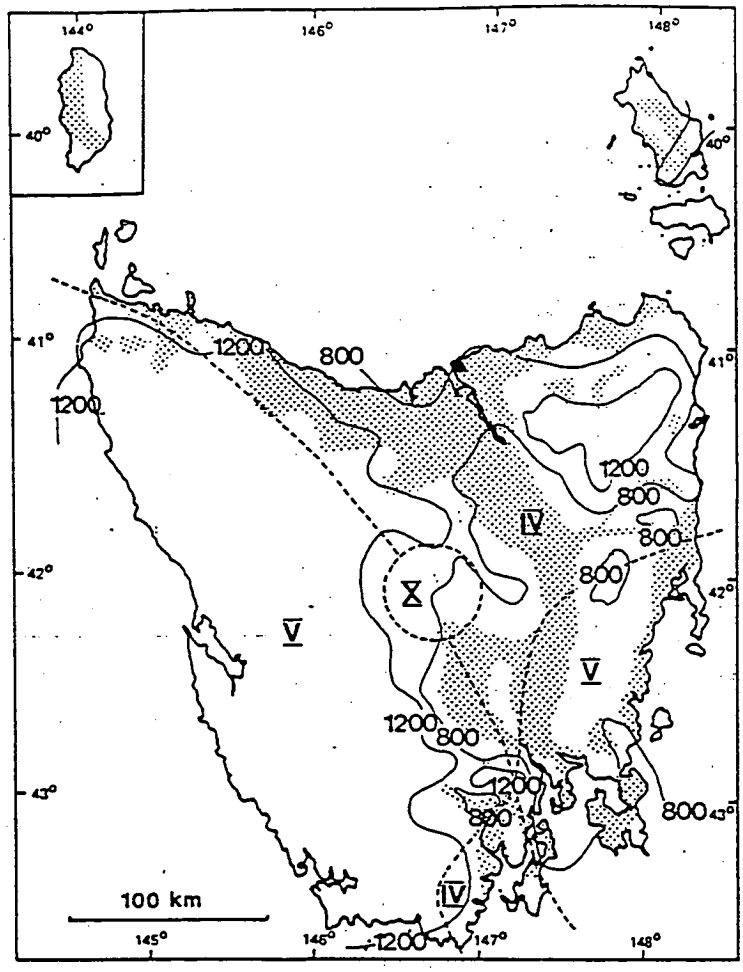
10.2. *O.* sp. *ambulans* gp.



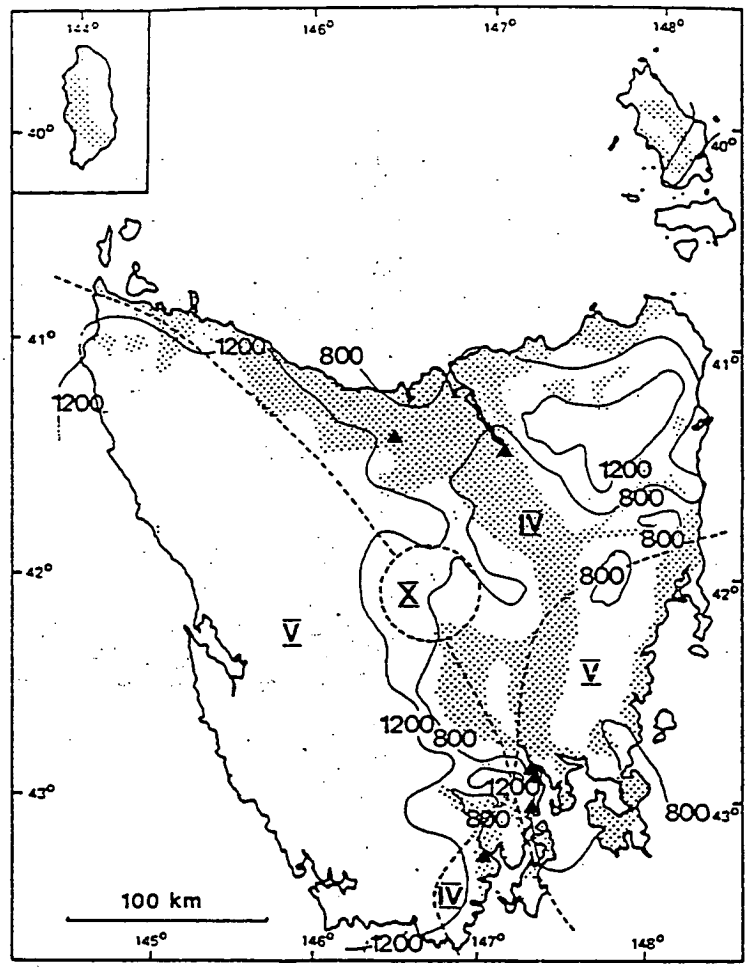
10.3. *O.* sp. *fimetarius* gp.



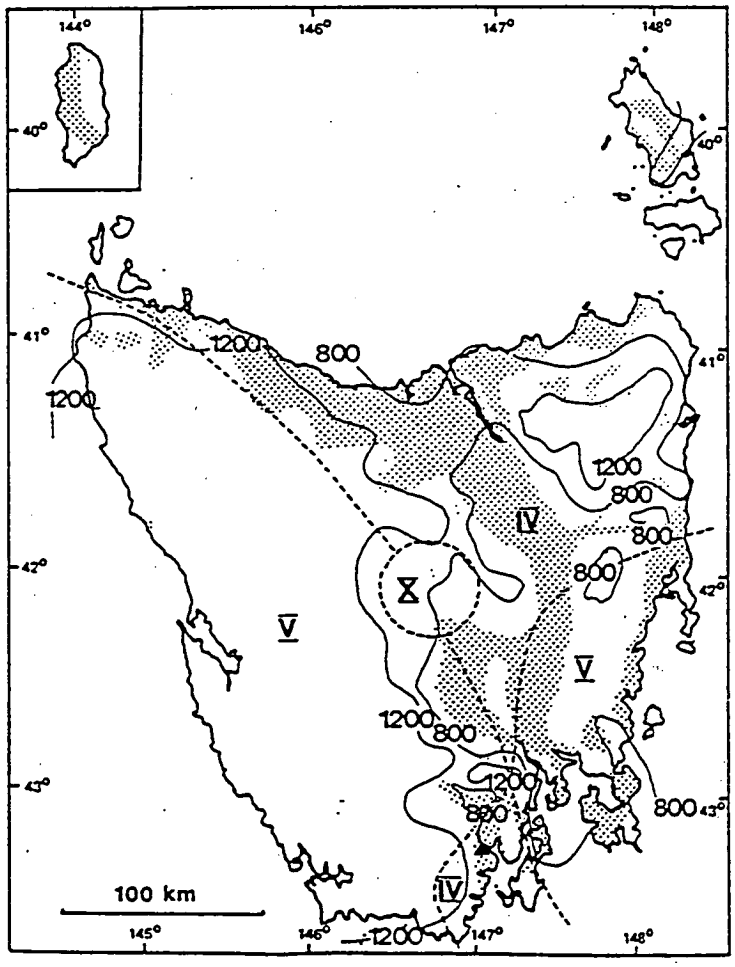
10.4. *Tullbergia* sp.



10.5. *Dinaphorura* sp.



10.6. *F. candida*



10.7. *P. minuta*

Cressy area were reported as showing patchy germination and poor establishment. Springtails were noted by farmers and samples were subsequently forwarded for identification. Both Onychiurus sp. armatus group and O. sp. fimetarius group were identified from the same samples. This identification was followed soon after by an inspection of 6 pea crops in the Cressy area.

Estimates of Onychiurus populations in each crop were made by taking 6 core samples randomly from within the rows of each crop to a depth of 10 cm and extracting the cores in the laboratory (see Chapter 2). Examination of Table 10.2 shows that numbers of Onychiurus were high, particularly in the crops numbered 1 and 2.

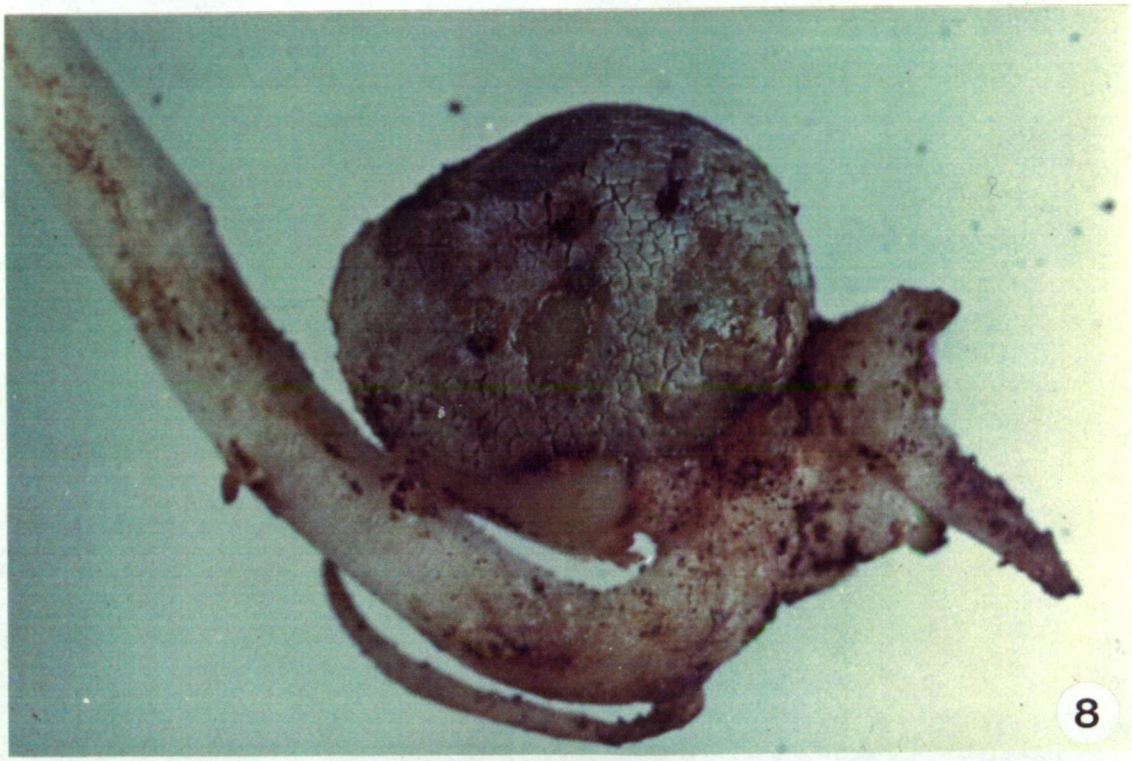
Table 10.2 Population estimates of Onychiurus spp. in soil ex. pea crops, Cressy, October, 1982.

Crop no.	Mean no.Onychiurus per core	Estimated no.Onychiurus/l of soil
1	344.0	1754.4
2	162.2	824.8
3	27.0	137.7
4	19.8	101.0
5	15.0	76.5
6	10.5	53.6

In all crops examined there were patches of stunted growth with the potential yield loss per crop estimated at 10-15%. Inspection of stunted pea plants particularly in crops 1 and 2 revealed damage that could be attributed to the feeding of Onychiurus, the main effect being to the developing tap root and its rootlets. The tap root was typically pitted and stunted and either bare of secondary rootlets or with poor lateral root development; in some cases it had been completely removed (Figs 10.8, 10.9). Onychiurus were seen to be numerous around the roots and in the decaying seed. At the time of examination, conditions in the crops were considered ideal for the development of Onychiurus. In each, the soils had previously been under pasture and were high in levels of organic matter. In addition, few pea plants were examined with normal nodulation and in many instances there was no nodulation on plants up to 120 mm high. This was indicative of low pH (Crush 1987) which is known to favour an increase in the abundance of Onychiurus (Hutson 1978; Bååth et al. 1980). Subsequent pH measurements of the soil from poorly nodulated crops in the Cressy district revealed levels in the range of 4.8-5.5, well below the minimum level of 5.7 recommended to enable adequate nodulation of field peas.

However, in crops 3-6 poor establishment was not attributed to Onychiurus. In these crops, cotyledons exhibited varying degrees of

Figs 10.8-10.9 Damage to roots of pea seedlings by Onychiurus spp.: (8) seedling with severed tap root; (9) tap root intact but secondary rootlets have been removed and there is poor development of lateral roots.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internal rotting with poorly developed tap roots and secondary roots. Subsequent pathological examination of samples taken from these crops showed infection by the fungal saprophyte Fusarium oxysporum and pathogenic Pythium spp., the presence of the latter species often being influenced by depth of sowing, with placement too deep increasing susceptibility to attack (Sampson pers. comm.). Farmers in the district tended to attribute the primary cause of all the problems to root-feeding springtails. This was not surprising because of the presence of Onychiurus which were easily visible in large numbers. As Onychiurus spp. were known to be primarily fungivorous and Fusarium spp. are saprophytic fungi, possible factors additional to low pH that may have predisposed the crops to attack were investigated.

(iv) Possible factors predisposing pea crops to attack by Onychiurus

(a) Sowing technique

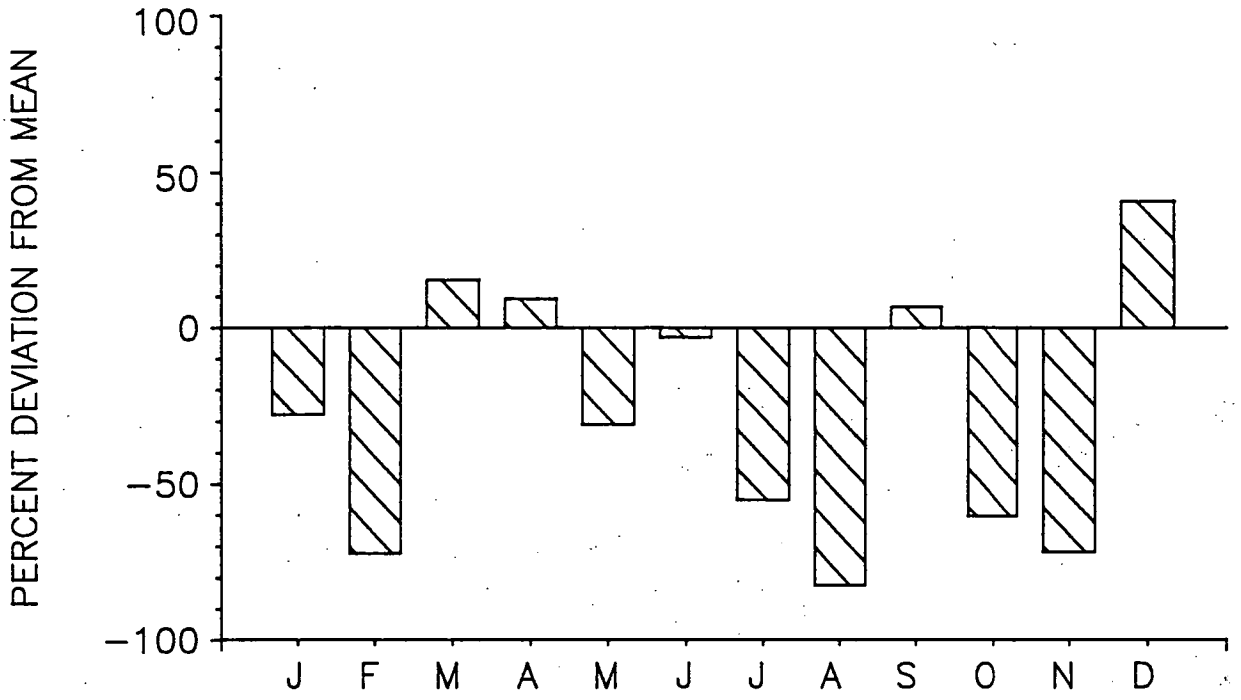
Investigations revealed that cultural techniques from the initial ploughing through to sowing did not generally differ from those practiced in most green pea production areas in Tasmania. As would be expected, there were differences in management techniques. Some growers pre-drilled fertiliser mixtures and sowed lime/superphosphate with the seed and others sowed NPK mixtures in direct contact with the seed. There were also variations in the depth of sowing from seed placed just below the surface in some instances and up to 20 mm deep in others. However, although there was nothing to indicate that any of these factors was primarily responsible for poorly developed pea seedlings, some of these may well have contributed to the loss of some plants or to the weakening of lesser developed plants, particularly in instances where the fertiliser may have been in direct contact with seed, in other than an optimum soil moisture regime.

(b) Weather

Relevant weather data for Cressy (1982) is shown in Fig. 10.10 and Table 10.3. The main sowing and establishment period for field peas at Cressy in 1982 was September-October. Rainfall recorded for the January-August period 1982 was 57.5% below the mean (Fig 10.10), and this could have been a major contributing factor to the problems that occurred. Soil humus decomposes slowly in the soil, however, the drier the soil and the longer it is kept dry before wetting, the greater the flush of decomposition (Russell 1961). Heterotrophic organisms require a suitable carbon substrate which is released from humus breakdown or killed cells. If soil is either sterilised or air dried and re-wetted this accounts for the flush in respiration or microbial proliferation (Lynch 1984). Any increase in the microbiological activity in the humus fraction would be attractive to Onychiurus spp., which would feed on the micro-organisms that would be associated with the breakdown of organic matter. The dry weather experienced up to the end of August 1982 at Cressy, followed by above average rainfall received during September (Fig 10.10) may therefore have been a stimulus for the build-up of large populations of

Fig 10.10 Deviations from mean rainfall recorded at Cressy Research Station, 1982-83.

1982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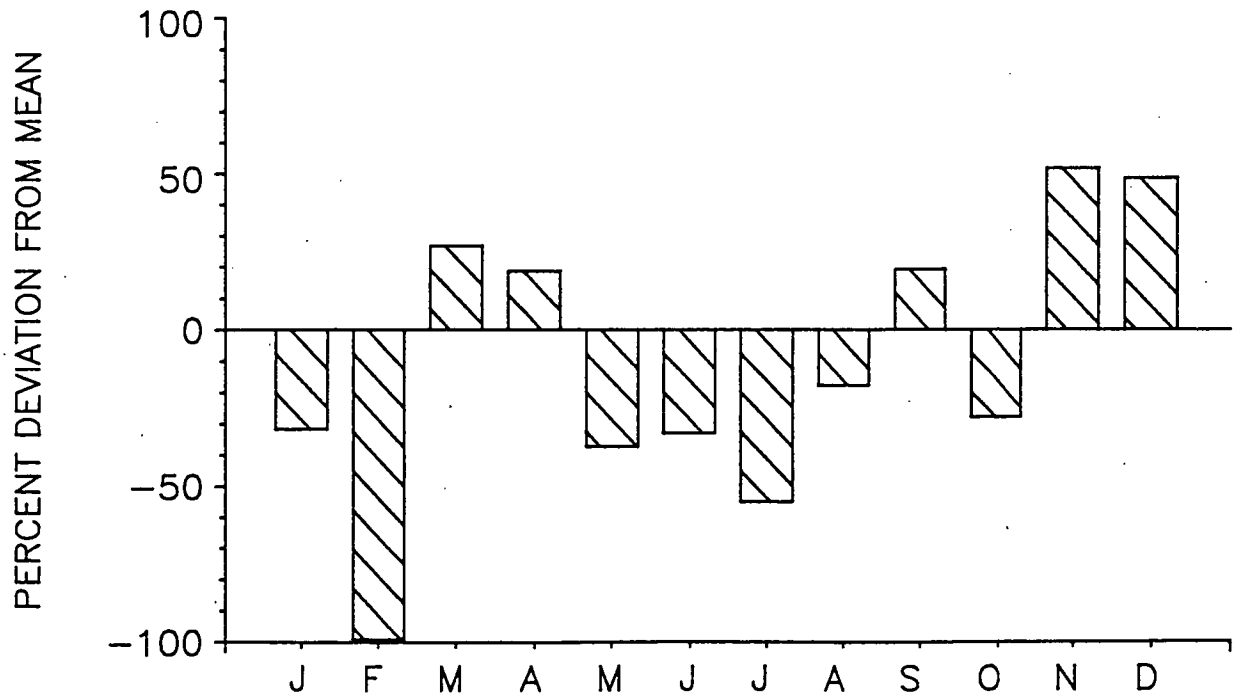
1983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soil micro-organisms and an associated increase in populations of Onychiurus spp.

Examination of Fig 10.10 shows that September was one of the few months during 1982 when rainfall was above average, and some paddocks were noted to have moisture levels that were adequate enough for normal germination and seedling establishment, even though they had not been irrigated. Nevertheless, a number of frosts were also reported and these were particularly heavy (Table 10.3). The effect of these frosts, together with the high evaporation, probably resulted in the low levels of soil moisture that were reported by some growers in the district. This factor was highlighted in one particular instance when part of a crop germinated and emerged within 7-8 days following sowing. Irrigation was then applied to germinate and establish the remainder.

(c) Seed quality

Crops observed were grown under contract and the companies provided the test certificate information on the seed lines of several crops inspected, which is presented in Table 10.4.

From information on the test certificates of the seed lines used for several of the growers, the seed in some instances was of moderate quality only. Moderate quality seed sown from September and throughout October and subjected to the environmental conditions experienced at Cressy during the 1982 season, would not have performed completely satisfactorily, even if all cultural factors had been ideal (Walker pers. comm.). However, although this factor may have played a part in the less than optimum germination it was probably only a contributing factor. Also, when seed count is considered with the less than optimum conditions existing at sowing time, determination of the correct sowing rate becomes important. Inquiries revealed that growers sowed insufficient seed to achieve the optimum establishment, of around 100 plants per square metre. Examples of this were: a crop was sown at 250 kg/ha, seed count 4623, germination 90%, conductivity C grade and hollow heart 19%; another was sown at 270 kg/ha with a seed count of 4330, germination 90%, conductivity C grade and hollow heart 24%. Walker (pers. comm.) considered that in these examples a sowing rate of at least 300 kg/ha would have been more appropriate to have achieved optimum plant establishment when test certificate data and the other factors at sowing time were taken into account. The field factor ultimately chosen to determine a particular sowing rate has to be carefully assessed on the basis of that certificate data, soil moisture and temperatures, seed bed condition and other cultural and environmental factors that exist at the time of sowing.

(d) Summary of possible contributing factors

The available facts suggest that a number of factors may have contributed to sub-optimal conditions for plant growth these included: (i) atypical

climatic conditions at sowing (low temperatures and variable soil moisture regimes), as well as the low rainfall received throughout the year, (ii) sub-optimal sowing rates for the conditions at the time, (iii) large variations in sowing depth within and between crops, (iv) seed of only moderate quality being used in some instances, (v) fertiliser placed in direct contact with seed and, (vi) reduced nodulation resulting from low pH levels.

It is suggested that these were the main factors that may have predisposed weakened plants to attack by fungi and Onychiurus spp.

(v) Damage by Onychiurus to field peas, Cressy, 1983
During November 1983, 6 pea crops were inspected that again showed symptoms of stunted growth and poor germination. Subsequent inspections showed the damage was similar to that recorded the previous year and attributed to Onychiurus spp. Core sampling from around damaged plants in each of the six crops revealed mean populations of 49.3 per core (251/l of soil).

Factors that may have contributed to the problems observed the previous year were also apparent in some of these crops. These included variations in sowing depth and the sowing seed mixed with fertiliser. Unlike the previous year, however, the seed used was reported to be of high quality (Orr pers. comm.). Of the six paddocks inspected 4 were sown in paddocks that had previously been under pasture, resulting in large quantities of noticeably undecomposed organic residues still present in the soil. The remaining 2 crops had been sown to peas the previous season. Once again nodulation was poor in all but one affected paddock, this being reflected in pH readings taken on soil samples in all 6 crops which gave values of 5.7 in all but one instance (mean = 5.0; range 4.5-5.7). Weather conditions recorded in 1983 also showed a similar pattern to that of 1982 (Fig 10.10, Table 10.3). In particular, rainfall for the January-August period was again well below normal (29%) and again followed by above average falls for September (19.3% above mean). The abundance of organic matter, low pH, coupled with lengthy periods of dry weather followed by significant falls of rain near sowing time were probably the main factors contributing to the build-up of large populations of Onychiurus in some crops. However, in all crops inspected, plants showed marked differences in their susceptibility to attack. Comparison of core samples (to a depth of 10 cm) taken in the same crops from the vicinity of healthy plants with those taken from the vicinity of damaged plants, showed no significant differences in mean numbers of Onychiurus (Table 10.5). This further suggests the involvement of a predisposing factor(s) and a link between plant vigour and severity of damage, vigorously growing plants apparently being less likely to succumb to attack than a weak one.

Table 10.3 Meteorological data recorded at Cressy Research Station during sowing and early establishment period for field peas at Cressy, 1982-83.

	1982		1983	
	September	October	September	October
No. of frosts/month	17	14	12	11
Coldest frost	- 6.2°C	- 5.3°C	- 5.3°C	- 4.1°C
Rainfall	64	22	71.6	40.4
% deviation from mean rainfall	+ 6.7	-60.4	+25.6	-29.1
Evaporation	69	120	70.2	97.6
R/E ratio	0.9	0.2	1.0	0.4

Table 10.4 Data on seed counts, germination, conductivity and hollow heart of pea seed lines sown at Cressy, 1982.

Seed line	Seed count	% Germination	Conductivity	Hollow heart %
1	4623	90	C	19
2	4311	99	B	5
3	n.a.	93	B	3
4	4330	90	C	24
5	4442	93	A	16
6	4400	92	B	8

Table 10.5 Comparison of Onychiurus numbers in core samples from healthy and stunted plants, Cressy, November 1983.

Sample no.	No. of Onychiurus/l of soil	
	Healthy plants	Stunted plants
1	132.4	132.4
2	101.8	585.5
3	753.6	127.3
4	168.0	71.3
5	66.2	127.3
6	10.2	173.1
Totals	1232.2	1216.9
Means	205.4	202.8

Table 10.6 Comparison of season means of rainfall, temperature and rainfall:evaporation (R/E) ratios for 1981-87 with long term data, recorded at Cressy Research Station.

Year	Season	Mean rainfall	Mean temperature	Mean P/E
1981	Summer	65.3	17.9	0.1
	Autumn	134.2	12.1	0.6
	Winter	269.0	6.9	3.1
	Spring	129.2	11.5	0.4
	Annual	597.7	12.1	1.1
% deviation from long term annual mean		-7.1	+6.0	+10.0
1982	Summer	109.2	16.8	0.2
	Autumn	146.7	12.3	0.6
	Winter	96.0	6.1	0.9
	Spring	100.0	11.5	0.3
	Annual	451.9	11.7	0.5
% deviation from long term annual mean		-29.7	+2.6	-50.0
1983	Summer	51.2	16.3	0.1
	Autumn	152.4	12.2	0.7
	Winter	125.8	6.7	1.4
	Spring	186.0	10.8	0.7
	Annnual	515.4	11.5	0.7
% deviation from long term annual mean		-19.8	+1.0	-30.0
1984	Summer	104.8	15.4	0.2
	Autumn	170.4	11.7	0.8
	Winter	210.1	7.0	2.4
	Spring	234.6	11.4	0.8
	Annual	719.9	11.4	1.1
% deviation from long term annual mean		-12.0	0	+10.0

Table 10.6 (cont.) Comparison of season means of rainfall, temperature and rainfall:evaporation (R/E) ratios for 1981-87 with long term data, recorded at Cressy Research Station.

Year	Season	Mean rainfall	Mean temperature	Mean P/E
1985	Summer	173.4	15.5	0.4
	Autumn	237.0	12.8	0.8
	Winter	140.8	6.8	1.8
	Spring	149.2	11.3	0.5
	Annual	700.4	11.5	0.9
% deviation from long term annual mean		+8.9	+1.0	-10.0
1986	Summer	99.5	14.7	0.3
	Autumn	173.0	12.0	0.8
	Winter	156.2	6.3	1.8
	Spring	184.2	10.8	0.6
	Annual	612.9	10.9	0.9
% deviation from long term annual mean		+4.7	+4.4	-10.0
1987	Summer	79.8	13.5	0.2
	Autumn	108.0	11.7	0.5
	Winter	104.2	6.6	1.3
	Spring	134.4	11.8	0.4
	Annual	426.4	10.9	0.6
% deviation from long term annual mean		-33.7	-4.4	-40.0
Long term				
	Summer	128	16.1	0.3
	Autumn	154	11.9	0.9
	Winter	196	6.5	2.2
	Spring	165	10.9	0.6
	Annual	643	11.4	1.0

Overall, the investigations reported here indicate that the poor growth in some pea crops at Cressy during the 1982 and 1983 seasons seemed to result from a complexity of factors in which some crops were grown under cultural conditions that predisposed some plants to attack by Onychiurus spp. Although species can now be regarded as potential pests of field crops in Tasmania, there have been no further reports of Onychiurus damage to field peas during the five years since these investigations were carried out.

Changes in cultural practices since then have only been marginal with perhaps more attention being given to correct sowing depth (Walker pers. comm.), however, (although the possible effects of weather factors have been discussed) it is interesting to compare annual figures of seasonal rainfall, temperature and rainfall/evaporation (R/E) ratios for 1982-83 with those for 1981 and from 1984-87. Examination of Table 10.6 shows that mean annual rainfall and R/E values for 1982-83 were well below average and lower than the values in 1981 and during the years 1984-86. Rainfall for 1987 was again well below average and although temperatures were also below mean and lower than those recorded in 1982-83, the annual R/E value was still 30% below average. Perhaps the particular combination of the unusual weather conditions prevailing during 1982-83 and the cultural practices being used on the Cressy pea crops were the main contributing factors to the problems that occurred. However, to what extent this is so remains open to speculation.

DISCUSSION

The surveys show that Onychiurus spp. are common inhabitants of soil in the Tasmanian culture steppe, with populations being generally more abundant and often associated with root damage in those soils high in organic matter and a low pH. The observation that large numbers were particularly evident in pea crops previously ploughed for pasture, was similar to that made by Heijbroek (1971) during his investigations of damage by Onychiurus to sugar beet in the Netherlands. He showed that multiplication of Onychiurus is enhanced by growing ryegrass and clover as a green manure crop, with large numbers being present in subsequent sugar beet crops following ploughing which increased the chance of root damage. However, the presence of large numbers of Onychiurus in the vicinity of healthy pea plants at Cressy shows that large numbers may occur in soil without necessarily inflicting damage. Onychiurus should be classed as a facultative rather than an obligate root feeder. Euedaphic Collembola feed primarily on decaying organic matter, bacteria, fungi, algae and nematodes (Christiansen 1964; Greenslade and Greenslade 1983) and one of their major roles in the soil ecosystem involves organic matter breakdown and the dissemination of soil fungi (Poole 1959; Hanlon and Anderson 1979; Wiggins et al. 1979). It is soil fungi that are probably one of the main food sources for Onychiurus spp, F. candida and P. minuta (Petersen 1971; Christen 1975; McMillan 1975, 1976; Booth and Anderson 1979), with species being attracted to fungi by the release of

volatile compounds from the fungal mycelium (Bengtsson et al. 1988). There are probably many cases, therefore, where the prime cause of poor seedling growth has been incorrectly attributed to Onychiurus, which may have been attracted in large numbers to already weakened plants attacked by fungal pathogens (Lawrence 1979). It is therefore logical to expect that populations of organisms within the plant rhizosphere (fungi, bacteria, algae) on which Collembola such as Onychiurus are known to feed, would influence collembolan activities (Wiggins et al. 1979). However, the interactions between the rhizosphere of a plant, the associated microflora and microarthropods (such as Collembola) and the subsequent effects on plant growth are extremely complex (Curl 1979, 1982). This association may vary according to a number of environmental factors including type of plant cover (pastures with dense root systems usually carrying higher populations of soil microarthropods than field crops), soil moisture levels (Wiggins et al. 1979), responses to both organic and inorganic fertilisers (Edwards and Lofty 1969) and soil pH (Hutson 1978; Bååth et al. 1980; Hågvar and Abrahamsen 1984; Hågvar 1984).

Exudates from plant roots and germinating seeds stimulate the growth of rhizosphere microflora. Many plant and environmental factors may influence amount and composition of exudate released to the rhizosphere. These include soil type and fertility, plant injury, stage of plant development and microbial activity at the root surface (Hale and Moore 1979). Exudation is known to be greater from stressed plants (Curl 1982), which may lead to increased activity of fungivorous soil animals such as Onychiurus that abound in organically rich soils and congregate where fungi would be most readily available (Farahat 1966). The complexities of the association between soil Collembola and rhizosphere micro-organisms is known to have both beneficial and detrimental effects on plant growth. Beneficial effects were clearly demonstrated by Curl (1979), whose studies showed that cotton roots growing in previously sterile soil suffered high mortality when infested with Rhizoctonia solani. When P. minuta and O. encarpatus were added to the same culture, they significantly relieved disease severity by the reduction in inoculum density, due to the species feeding on the pathogenic fungus. Soil Collembola also play a role in nutrient recycling. Nutrient level of the fungus can effect feeding behaviour (Booth and Anderson 1979) and by their feeding on a range of microflora, they return nutrients to the soil (Coleman et al. 1983). Warnock et al. (1982) showed that the presence of F. candida had a negative influence on the leek (Allium porrum) by affecting the plants mycorrhizal association. Plant growth was stimulated by mycorrhizal infection but in the presence of F. candida plants grew little better than uninfected plants. They found that phosphate uptake was significantly reduced by the grazing of F. candida on external hyphae, thus causing the plant mycorrhizal association to be ineffective. Finlay (1985), however, showed that although grazing of the external mycelium may reduce the efficiency of the mycorrhizal

association, effects on plant yield and nutrient uptake seem to depend on collembolan density, as low grazing intensities seemed to stimulate mycorrhizal plant growth. It was postulated that this could have partly resulted from selective feeding by F. candida on other microbial populations. Selective grazing by Collembola may be an important factor in determining field distribution of fungi (Christen 1975; Parkinson et al. (1979); Newell 1984), and the occurrence of ingested and passed pathogens could be significant in an area if large collembolan populations were present (Christen op. cit.).

In an extensive agricultural situation where weeds are absent, pesticide and organic matter levels are often high, contributing to a low pH. As euedaphic Collembola may flourish under such conditions, high populations can occur if moisture is optimal.

Species of Onychiurus that are often attracted to the plant rhizosphere in large numbers by the presence of micro-organisms, may occasionally be wrongly accused of being the primary cause of damage to plants that are in poor health. Although these species may have the potential to reduce yields by feeding on plant roots, such feeding is considered non-selective and seems to result primarily from their activities as mycophages. Conclusions made on the pest status of euedaphic species, therefore, are the same as those that apply for some surface-active species other than S. viridis as discussed in Chapter 9. Because of the complexities of the soil-plant ecosystem, any association of euedaphic Collembola with plant damage needs to be thoroughly investigated as there may be other factors involved.

CHAPTER 11

FIELD TRIAL TO INVESTIGATE SUSCEPTIBILITY OF *ONYCHIURUS* SPP. TO CHLORPYRIFOS

INTRODUCTION

Collembola vary considerably in their susceptibility to pesticides (Edwards and Thompson 1973). Such variations may be inter-specific, therefore toxicity data cannot be easily extrapolated from one species to another or between related chemicals (Tomlin 1975, 1977). A number of organochlorine pesticides including lindane and dieldrin are reported as being effective against Onychiurus spp. (Scott 1964; Heijbroek 1971), however, Baker and Dunning (1975) obtained poor control of Onychiurus spp. with dieldrin during field trials on sugar beet. Of the carbamates, aldicarb has provided adequate protection of sugar beet from O. armatus following seed furrow treatment (Heijbroek 1971; Heijbroek et al. 1980), but there is conflicting evidence as to the efficacy of this pesticide (Edwards 1980). Carbofuran was found to reduce populations of Onychiurus pseudarmatus Folsom, resulting in increased yields of spinach (Getzin 1985) and Heijbroek (1971) found that seed treatment of sugar beet with carbaryl can be effective in preventing damage to Onychiurus in cases of light or moderate infestations. Results obtained from the use of organophosphate compounds have also been varied. Phorate was shown by Way and Scopes (1968) to cause population decreases in Onychiuridae, however, Edwards et al. (1968) observed increases in number of soil Collembola following applications of chlorfenvinphos, although its effects on Onychiuridae were inconclusive.

No previous work has been done on control measures for Onychiurus spp. in local field situations in Tasmania (or on the mainland), because of their low pest status. However, following the observations of damage to field peas during the 1982/83 surveys, a trial was undertaken during the spring of 1984 to obtain information on the susceptibility of Onychiurus to an application of the organophosphate chlorpyrifos, and to determine if growth responses in field peas could be obtained as a result of this treatment. Chlorpyrifos was chosen because it was a relatively cheap pesticide, readily available to farmers and already known to be an effective control measure against a number of root feeding pests (Phimister pers. comm.). In addition, there were no known published field trials from overseas on the efficacy of this pesticide against Onychiurus spp. Although the overseas work reviewed above had shown some chlorinated hydrocarbon pesticides to be effective, these were not considered for use on field peas because of the long withholding periods and the possibility of taint problems. Furthermore, these products were, at the time, being phased out from agricultural use in Tasmania.

This Chapter (i) presents the results of a field trial conducted in the Cressy district during 1984 to assess the use of the organophosphate chlorpyrifos in controlling Onychiurus spp. and (ii) discusses factors affecting the efficacy of pesticide control measures for these species.

MATERIALS AND METHODS

It was difficult to locate a suitable trial site during the 1984 growing season as there were no reports of Onychiurus being associated with crop damage, however, a site was selected at Bishopsbourne, near Cressy. At Bishopsbourne ("Vron") 8 trial plots 10 m x 3 m (each 3.5 m apart) were erected in a paddock just prior to being sown with field peas. Treatments included a standard seed treatment (Captan) (Control) and a standard seed treatment plus chlorpyrifos. Each plot was divided into 4 replicates there being two treatments in each replicate. For the insecticide treatment, chlorpyrifos was applied at the rate of 2 l 50% e.c./ha using a precision spayer. After spraying, the pesticide was rotovated into the surface soil. Pre- and post-spray sampling of the control and chlorpyrifos treated plots for Onychiurus was carried out by taking random core samples. Methods of collection, extraction and examination of samples is described in Chapter 2. An analysis of variance was used on the results to determine any treatment effects. Mean yields of peas from treated and control plots (kg/ha) were obtained at harvest. Meteorological data was obtained from Cressy Research Station.

RESULTS

Counts of Onychiurus from pre- and post-spray core samples from the Bishopsbourne ("Vron") site are summarised in Table 11.1. Comparison with Tables 10.2 and 10.5 show that numbers of Onychiurus were much lower than those found in survey samples taken from pea crops in the Cressy area during 1982-83. Comparison of post-spray treated and control plots at "Vron" shows that mean Onychiurus numbers were lower in the treated plots, however, analysis of the data showed that this difference was not significant either before or after treatments (Table 11.1). In the first post-spray sample, a steep fall in the mean population of both treated and control plots was recorded. Fluctuations continued throughout the sampling programme, with mean numbers of Onychiurus at the second and final post-spray sample dates showing an increase over mean numbers recorded in previous samples. The yields of peas recorded in both treated and control plots (Table 11.2) were approximately twice the commercial yield.

DISCUSSION

There was no evidence from the trial that chlorpyrifos was an effective treatment for reducing Onychiurus populations. The observations were hindered by the large reduction of numbers in both treated and control plots after the initial pre-spray samples and the fluctuating numbers in subsequent samples. Chemical control of euedaphic species can be considered difficult not only because of the likelihood of poor soil penetration by the pesticide, but also because the activities of Onychiurus spp. are affected by soil temperature and humidity (Winner and Schaufele 1967). This causes considerable fluctuation of populations at or near the soil surface and results in downward migration of Onychiurus

spp. as the surface soil dries out (Hassal et al. 1986; Heijbroek 1971). Heijbroek (op. cit.) found the presence of Onychiurus in the top 3-5 cm of soil in sugar beet crops in the Netherlands during spring is largely determined by the moisture content, as species are highly susceptible to dessication. As a consequence, damage was often considerable during a wet spring whereas during a dry spring, Onychiurus migrated to a greater depth, away from germinating seeds and seedlings. He showed that the efficacy of pesticides for control of Onychiurus also seemed to be greatly influenced by temperature, as Onychiurus could hibernate in the soil at depths of up to 70 cm and migrate into the seed bed during early spring when temperatures rose above 5[C; Onychiurus were most sensitive to pesticides at temperatures below 10[C, whereas lower mortalities were observed in laboratory trials conducted at room temperature.

Obviously, further trials would be needed to determine the efficacy of any chemicals that could be used to control Onychiurus spp. in Tasmania, if it was considered that chemical control was appropriate. For example, the efficacy of the granular form of chlorpyrifos ('Suscon') could be investigated. The chemical is registered in some Australian states (e.g. Queensland, for control of cane grub) but not in Tasmania. Use of the granular form would overcome the problem of the lack of persistence with the emulsifiable concentrate formulation, as a range of granular formulations are available which enable the active ingredient to be released over periods ranging from 150 days to 3 years. Furthermore, the granules can be drilled directly into the furrows with the seed. However, it is, of course, also possible that chlorpyrifos is ineffective against Onychiurus no matter what form it is in.

In Europe, there is now a change to more integrated forms of control of sugar beet pests. For Onychiurus this includes avoidance of clover and grass crops in rotation and promoting a reduction of Onychiurus spp. in beet rows by decreasing the level of weed control (Heijbroek et al. 1980). Seed bed compaction before drilling is also known to be beneficial by hindering Onychiurus migration as compacted soils are known to have a repellent effect (Didden 1987). Heijbroek et al. (1980) discuss another method which involves treatment of the space between the rows of sugar beet seedlings with molasses, which stimulates the growth of microflora which attracts Onychiurus. Although Onychiurus populations are concentrated away from the seedlings, the method is combined with supplementary seed treatment as it cannot prevent complete damage. Perhaps in the future, use will be made of aggregation pheremones which have been shown to occur in Onychiurus armatus; these trigger gregariousness and appear to be more or less species specific (Joosse and Koelman 1979).

The high yields recorded in both treated and control plots indicated the presence of Onychiurus did not significantly affect the growth of peas at the Bishopsbourne site. However, the estimated mean pre-spray counts of

Table 11.1 Results of chlorpyrifos spray trial at Bishopsbourne ("Vron') showing mean numbers of Onychiurus per core sample.

Rep. No.	Treatment	Mean no./ pre-spray 5.12.84	Mean no./post-spray sample 12.12.84	3.1.85	21.1.85	30.1.85
1	Unsprayed	7.7	3.5	1.8	3.5	4.3
	Sprayed	9.5	1.3	2.0	4.5	5.0
2	Unsprayed	3.0	1.5	2.5	2.5	13.3
	Sprayed	4.5	0.8	0.3	0	2.9
3	Unsprayed	8.0	3.0	4.3	3.5	1.5
	Sprayed	8.0	2.3	3.8	0	2.5
4	Unsprayed	1.0	2.3	6.5	0.8	2.8
	Sprayed	5.0	1.3	3.8	1.5	3.3
Untreated means		4.9)) 5.9*	2.6	3.8	2.6	5.5
Treated means		6.8)	1.4	2.5	1.5	3.4
LSD Treatments/time		3.49				

* Mean number of Onychiurus spp. population in trial plot = 5.9 which is equivalent to 59 specimens per 1 of soil (i.e. to a depth of 5 cm).

Table 11.2 Mean yields of green peas (kg/ha) at Bishopsbourne ("Vron").

Date of sowing	Date of harvest	Commercial yield (kg/ha)	Mean plot yields (kg/ha) Unsprayed	Sprayed
5.12.84	19.2.85	4784	9340	9410

Onychiurus at 59/1 of surface soil and subsequent mean counts of 36.7/1 in unsprayed plots during the remainder of the trial (Table 11.1) were considerably higher than the densities of only 10/1 of top soil reported by Brown (1984), the population threshold above which damage was observed to the roots of sugar beet in England. The lack of damage observed in this trial is another indicator that the infliction of injury to plant roots by Onychiurus is governed by a complexity of inter-related factors. These factors may be partly controlled by good cultural practices. Changes in sugar beet husbandry in European countries accentuated the problems of damage to this crop (Brown 1983). For instance, drilling distance in rows was increased and weed control was improved by herbicide use. This led to pests causing more damage than they did in the past, partly because the weeds which may have offered an alternative food supply for potential pests were no longer present, causing populations to concentrate around the sugar beet. Increased pesticide use also had negative effects on the soil ecosystem resulting in decreases in populations of potential arthropod predators (Heijbroek et al. 1980).

CHAPTER 12

IDENTIFICATION, DISTRIBUTION, HABITS AND SIGNIFICANCE OF *HYPOGASTRURA* SPP. IN THE TASMANIAN CULTURE STEPPE

INTRODUCTION

In the culture steppe, species of Hypogastrura are probably noticed more than other Collembola by the casual observer because of their tendency to aggregate in large numbers on water surfaces, footpaths and on the surface soil of home gardens and agricultural land. As a result they are the frequent subject of public enquiries as to their identification and the reason for the manifestation of such large numbers. In addition they are frequently associated with crop damage as specimens are often seen feeding on damaged or decaying plants, either in home gardens or agricultural areas.

During this study 298 hypogastrurid specimens collected from a variety of habitats throughout the State were examined. This Chapter (i) lists the species of Hypogastrura present in Tasmania with particular reference to the culture steppe, (ii) provides data on their seasonal activity and statewide distribution and (iii) discusses their biology and pest status and importance as ecological indicators. A key to the Tasmanian species is given in Chapter 13.

MATERIALS AND METHODS

(i) Collection

Specimens were collected and examined from mainly agricultural and urban environments. Some collections from native vegetation enabled comparison of Hypogastrura species present in this habitat with those in the culture steppe. Samples from agricultural land and native vegetation were collected using either the suction technique, pitfall trapping, or by litter extraction in Berlese or Tullgren funnels, the methodology being detailed in Chapter 2. Samples examined from urban environments (home gardens, glasshouses and nurseries) and from some coastal areas, were usually hand collections brought in by colleagues or members of the public for identification.

(ii) Identification

Species were identified initially by collaboration with Greenslade (South Australian museum) (see Chapter 13) and reference to the keys of Womersley (1939), Stach (1949), Gisin (1960), Fjellberg (1980) and Christiansen and Bellinger (1980a). Reference to these authors enabled construction of a key to the Tasmanian species. Specimens were cleared using the technique described in Chapter 2, then examined under a Phase Contrast Microscope. A Cambridge Scanning Electronic Microscope was used to obtain micrographs of some of the main characters used to separate species (details of specimen preparation for the SEM are outlined in Chapter 2).

(iii) Distribution and phenology

Distribution of species was examined in relation to the climatic zones of Walter and Lieth (1967) and in relation to the 800 and 1200 mm isohyets. Although Hypogastrura species were uncommon in the monitored plots in

high rainfall pastures at Moriarty, Elliott and Flowerdale (Chapter 8), collection data obtained during the pasture surveys and from other sites were used to determine periods of seasonal activity. The data were expressed into contingency tables and analysed using the log-linear model technique of generalised linear models (McCullagh and Nelder 1983) as done for the species discussed in Chapters 3, 5 and 8.

RESULTS

A total of 8 species of Hypogastrura were identified and keyed (see Chapter 13). Table 12.1 summarises species collection sites in both the culture steppe (the majority of which were from pastures and field crops) and native vegetation. Species collection sites in pastures are illustrated in Figs 8.34 - 8.41 and in field crops, Figs 9.22 - 9.27. The only species commonly found in native vegetation was H. purpurescens which was rare in the culture steppe. Although the remaining 7 species were mainly confined to the culture steppe there were a few records of H. sp. cf. engadinensis, H. denticulata and H. gibbosa from native vegetation. These were usually from areas close to land development and/or sites frequently disturbed by human activity. The most common species in the culture steppe were H. denticulata, H. sp. cf. engadinensis, and H. vernalis which were located in all climatic regions (defined in Chapter 3). H. manubrialis was also widespread but unlike the former species was collected only from pastures or field crops. H. viatica was only recorded from agricultural land near the coast, from coastal urban areas or directly from sites near the shoreline or amongst shore debris. The few records of H. assimilis indicate that this species is rare in Tasmania.

Table 12.2 lists specific habitats recorded for each species. All are hemiedaphic occurring mainly in surface litter and soil, large numbers often being recorded in moist soils high in organic matter content. Although 4 species were observed feeding on decaying plant material (Table 12.3) there was no field evidence of species causing primary damage.

Specific instances of species aggregating in large numbers are presented in Table 12.4, the most commonly recorded being H. vernalis. Species were usually observed swarming or aggregating in moist conditions or after heavy rain amongst compost (particularly in home gardens), on cement or floating on the surface of puddles in urban areas or on agricultural land.

Results of analysis of the pasture collection data are presented in Table 12.5. Only the results for H. denticulata, H.sp. cf. engadinensis, H. manubrialis and H. vernalis are included as numbers of the occurrence of other species in pasture were too low to enable any significant relationship to be determined. The results show that H. sp. cf. engadinensis, H. manubrialis and H. vernalis all showed a significant

Table 12.1 Records of *Hypogastrura* spp. in the Tasmanian culture steppe and native vegetation.

Species	Agriculture		Urban			Littoral		Native Vegetation			
	Pasture	Field crop	Home gardens (compost, damaged plants, lawns)	Glasshouses	Aggregating or swarming on surfaces (cement, floating on water	Beach litter, seaweed, brackish water	Disturbed forest, other vegetation	Wet sclerophyll /rainforest	Dry sclerophyll	Other undisturbed vegetation	Total records per species
H. (C.) denticulata	37	14	5	2	3	0	1	0	0	0	62
H. (C.) sp.cf. engadinensis	38	9	5	1	3	0	9	1	0	0	66
H. (C.) gibbosa	5	4	3	0	0	0	5	1	1	0	19
H. (H.) assimilis	5	0	2	0	0	0	0	0	0	0	7
H. (H.) manubrialis	17	11	0	0	0	0	0	0	0	0	28
H. (H.) purpurescens	2	0	0	0	0	1	8	14	4	4	33
H. (H.) vernalis	32	25	5	0	9	0	0	0	0	0	71
H. (H.) viatica	0	5	4	0	1	2	0	0	0	0	12
Total records per habitat	136	68	24	3	16	3	23	16	5	4	298

Table 12.2 Specific habitats recorded for Hypogastrura spp. in Tasmania.

Species	Recorded habitat
H. (C.) denticulata	Surface soil and litter of pasture, field crops, home gardens; dung; floating on water; decaying gladioli bulbs; beach litter; damp leaf litter in disturbed wet sclerophyll forest.
H. (C.) sp.cf. engadinensis	Surface soil and litter of pasture, field crops, some gardens; floating on water; vegetable compost (cocoa bean husks), horse and fowl manure; ground litter beneath Pinus radiata; damp leaf litter, wet sclerophyll, rainforest and sub-alpine vegetation.
H. (C.) gibbosa	Surface soil and litter of pasture, field crops and home gardens; rotting vegetation (home gardens); decaying onions (home garden); leaf litter, dry sclerophyll forest; leaf litter and mosses, wet sclerophyll forest;Pinus radiata.
H. (H.) assimilis	Surface soil and litter of pastures and home gardens.
H. (H.) manubrialis	Surface soil and litter of pastures and field crops.
H. (H.) purpurescens	Leaf, soil litter and mosses of rainforest and wet and dry sclerophyll forest; litter from sub-alpine vegetation; floating on river surface (drift net samples in rainforest); ground litter beneath Pinus radiata; Australian salt grass (Distichlis distichophylla) and associated litter near beach.
H. (H.) vernalis	Surface soil and litter of pastures, field crops and home gardens (and lawns); rotting vegetation (field crops); floating on water; in manure (fowl houses, birds aviaries); swarming on concrete; entering houses.
H. (H.) viatica	Surface soil and litter of field crops and home gardens (straw mulch, rotting vegetables); in coastal areas floating on brackish water and on kelp.

Table 12.3 Species of *Hypogastrura* associated with decaying plant material.

Species	Date	Plant	Location
H. vernalis	. . 88	Onions	Onion crop, Devonport
H. viatica	15.4.82	Onions	Home garden, Snug
	10.2.86	Onions	Onion crop, Devonport
H. gibbosa	29.3.84	Onions	Home garden, Hobart (Lutana)
	17.6.76	Cabbages, potato tubers	Home garden, Hobart Home garden, Hobart (Chigwell)
H. denticulata	11.5.81	Gladioli bulbs	Nursery, Kingston

Table 12.4 Identification of Hypogastrura spp. reported as aggregating in the Tasmanian culture steppe.

Species	Date	Season	Locality	Report
H. vernalis	22.4.77	Autumn	George Town	Swarmining on concrete.
	18.4.78	Autumn	Fort Direction	Large numbers floating on water.
	30.5.78	Autumn	Sassafras	Large numbers floating on water in furrows of ploughed field.
	10.1.79	Summer	Primrose Sands	Swarming on concrete.
	3.5.79	Autumn	Glenorchy	Large numbers observed in home garden.
	20.8.79	Winter	Lindisfarne	Large numbers observed in home garden.
	23.6.80	Winter	Port Sorell	Large numbers floating on water.
	29.5.84	Autumn	Latrobe	Swarming on concrete and floating on puddles.
	13.9.84	Spring	Kempton	Swarming on surface soil of agricultural land.
	5.2.85	Summer	Scottsdale	Large numbers reported around and inside house.
	25.5.87	Autumn	George Town	Reported entering factory.
H. viatica	25.10.67	Spring	Wesley Vale	Large numbers observed in open drain.
	13.7.77	Winter	Dunalley	Large numbers in mulch at the base of strawberries.
	18.8.77	Winter	Ulverstone	Large numbers observed in home garden.
	23.8.77	Winter	Cremorne	Large numbers observed in home garden.
	30.10.78	Spring	Launceston	Large numbers observed in home garden.
	29.6.86	Winter	Sandford	Aggregating on brackish water.
H. denticulata	2.8.76	Winter	Longford	Large numbers floating on a puddle.
	23.8.76	Winter	Deloraine	Large numbers in glasshouse amongst manure used as compost (together with H. engadinensis).
	22.4.77	Autumn	George Town	Swarming on damp cement.
H. sp.cf. engadinensis	2.8.76	Winter	Longford	Large numbers floating on a puddle.
	23.8.76	Winter	Deloraine	Large numbers in glasshouse amongst manure used as compost (together with H. denticulata).
	25. 6.80	Winter	New Norfolk	Large numbers in home garden.
	22.12.81	Summer	Launceston	Swarming on path near garden.
	29.5.84	Autumn	Latrobe	Swarming on concrete and floating on puddles.
H. assimilis	20.2.76	Summer	Montrose	Large numbers observed in home garden.

Table 12.5 Frequency of occurrence and seasonality of Hypogastrura spp. in low and high rainfall pastures based on survey data.

Species	Season	% High rainfall	% Low rainfall	% Totals
H. (C.) denticulata	Spring	9.1	31.3	15.0
	Summer	5.9	4.8	5.5
	Autumn	17.5	7.1	15.6
	Winter	0	13.2	10.6
	Totals	11.3	13.5	12.1
	X^1_2 (high/low) = 0.24 (n.s.)			
	X^1_3 (seasonal) = 4.16 (n.s.)			
H. (C.) sp.cf. engadinensis	Spring	6.8	18.8	10.0
	Summer	0	0	0
	Autumn	7.9	0	6.5
	Winter	11.1	39.5	34.0
	Totals	6.0	20.2	11.3
	X^1_2 (high/low) = 10.86**			
	X^1_3 (seasonal) = 32.87**			
H. (H.) manubrialis	Spring	4.5	6.3	5.0
	Summer	0	0	0
	Autumn	0	0	0
	Winter	0	31.6	25.5
	Totals	1.3	14.6	5.0
	X^1_2 (high/low) = 16.83**			
	X^1_3 (seasonal) = 34.87**			
H. (H.) vernalis	Spring	2.3	18.1	8.3
	Summer	0	4.8	1.8
	Autumn	7.9	28.6	11.7
	Winter	0	36.8	29.8
	Totals	4.0	24.7	11.7
	X^1 (high/low) = 22.74**			
	X^1_3 (seasonal) = 20.48**			

Significance Level: X^1_2 ,5% = 3.84 X^1_3 ,5% = 7.81
X^1_2 ,1% = 6.63 X^1_3 ,1% = 11.3

preference ($P < 0.001$) for the drier pasture ecotype. This preference was also associated with a significant seasonal component ($P < 0.001$). Analysis of the data for H. denticulata showed no significant relationships. The majority of collections of H. sp. cf. engadinensis, H. manubrialis and H. vernalis were from the dry pasture ecotype during winter months. Winter activity was therefore a major contributor to the significance level of the seasonal component for these species. In high rainfall pastures only H. sp. cf. engadinesis was collected in winter. Summer collections of all species were low in both ecotypes.

Seasonal distribution of all collection records in the culture steppe for each species is shown in Table 12.6. Data for the most common species (H. vernalis, H. sp. cf. engadinensis, H. denticulata and H. manubrialis) again indicate that summer is the period of lowest activity with activity relatively high during the other seasons, although collections for H. manubrialis in autumn were low. Data from native vegetation is not included in Table 12.6 because of the habitat differences, however, Howard (1975) showed that total collembolan numbers (no data was given for individual species) remain almost constant throughout the year (apart from a slight summer maximum) in the stable environment of Tasmania's wet forests where conditions are continuously damp.

DISCUSSION

The Hypogastrura species recorded in the Tasmanian culture steppe are the same as those recorded from mainland States. As the genus is predominantly holarctic and the Australian species occur in Europe, it is probable that all have been introduced (Greenslade in press(a)). The genus Hypogastrura is one of the most archaic genera in the Collembola, so it is not suprising that altogether it includes about 100 cosmopolitan species (Yosii 1960). H. manubrialis, H. viatica and H. purpurescens are known cosmopolites having been recorded throughout Europe as well as in Africa and the Americas whereas overseas records of H. assimilis, H. denticulata, H. engadinensis, H. gibbosa and H. vernalis are mainly European (Salmon 1964). H. purpurescens was the only species that was common in native vegetation in Tasmania and is well established at some sites, particularly in the wet forest environment. The species may have been introduced into some wilderness areas as a result of minor disturbances (eg. bushwalkers,survey parties). River transport may also have enabled establishment in less accessable areas as the species was frequently identified in drift net samples taken from Tasmanian rivers (Table 12.2). The results for the other species suggest they are either absent or rare in wet forests. Perhaps some are less tolerant of the wet conditions that exist there. This would be consistent with the preference for pastures in low rainfall areas of the culture steppe shown by H. sp.cf. engadinensis, H. manubrialis and H. vernalis. However, the ubiquity of H. manubrialis, H. viatica and H. purpurescens on a global scale is indicative of the ability of Hypogastrura species to disseminate. Their ability to survive on water surfaces because of a

Table 12.6 Seasonal distribution of collection records of *Hypogastrura* spp. in the Tasmanian culture steppe.

Species	Distribution of collection records per season				
	Summer	Autumn	Winter	Spring	Total
H. (H.) vernalis	9	18	27	17	71
H. (C.) sp. cf. engadinensis	3	10	24	19	66
H. (C.) denticulata	7	18	11	25	61
H. (H.) manubrialis	1	1	13	13	28
H. (H.) viatica	2	1	5	4	12
H. (C.) gibbosa	2	1	7	7	17
H. (H.) assimilis	1	1	1	4	7
H. (H.) purpurescens	2	1	0	0	3

hydrophobic cuticle (Goto 1957) has probably played a major role here. In addition H. viatica was shown by Mertens et al. (1983) to be able to complete its life cycle in an aquatic environment and is a well known inhabitant of marsh lands and littoral areas in Europe (Gisin 1960; Remmert 1960). Studies by Britt (1951) suggest that other hypogastrurid species adapt to breeding in an aquatic environment.

Although H. denticulata showed no preference for wet or dry pasture ecotypes, the significant preference for the drier pasture ecotype shown by H. sp. cf. engadinensis, H. manubrialis and H. vernalis was less expected because of this ability of some Hypogastrura species such as H. purpurescens to thrive under cool, damp conditions. However, the result is supported by the lack of Hypogastrura specimens taken in core samples in the monitored pasture plots at Moriarty, Elliott, and Flowerdale. In field crops (oil poppies) at north-west sites, 6 species were collected from pitfall traps during spring (Chapter 9). Even so, activity of all species was low apart from H. vernalis which showed moderate to high activity in early spring. Perhaps in these higher rainfall areas (> 800 mm per annum) some species may prefer the more open field crop environment to a pasture. However, in this case such comparisons are probably irrelevant as the alcohol used in the traps is known to be an attractant to Hypogastrura species (Greenslade and Greenslade 1971).

It is also possible that sampling of herbage was not the best method of collecting Hypogastrura species in pastures. The explanation for this involves the presence of sheep as the dominant grazing animal in the drier pasture ecotype, as opposed to cattle in the wet pasture ecotype and the presence of cattle dung pads. Snowball (1944) found that many Collembola, particularly the Hypogastruridae are involved in dung decomposition and can complete their entire life cycle in dung. Work by Davidson (1979) showed that H. manubrialis exhibited a strong preference for dung itself, with population densities at pad sites exceeding those in soil by a factor greater than 1000. If H. sp. cf. engadinensis and H. vernalis also have high affinities for dung, perhaps the inclusion of dung pad samples would have given a more accurate assessment of species presence (or absence) in the predominantly cattle grazed wet pasture ecotype.

The lack of Hypogastrura species other than H. purpurescens in undisturbed native vegetation and the recording of H. sp. cf. engadinensis at a similar frequency to H. purpurescens in disturbed native vegetation was an interesting result. It suggests that Hypogastrura species would serve as useful ecological indicators in monitoring the effect of possible environmental deterioration, following the alteration of a previously stable ecosystem by activities such as clear-felling and mining. In particular, the ability of species to build up in large numbers under favourable conditions would make them highly competitive and able to become well established in disturbed vegetation

at the expense of native species. Conversely, the success of site rehabilitation could be gauged by the ability of native species to re-colonise, with a possible fall in the number and/or perhaps diversity of Hypogastrura species.

Greenslade and Greenslade (1984), although not specifically referring to Hypogastrura, suggested that Collembola would be ideal biological indicators because they fitted a number of criteria which included (a) being ubiquitous and having wide distributions on a continental scale, (b) concentration of populations at the soil surface, (c) representation in any locality by a substantial number of species, (d) being easy to sample and responsive to habitat variables, and (e) being easily identified to species level.

Using the classification of Greenslade and Greenslade (1987), the Hypogastrura species identified here can be classed as r strategists on the macroscale (because of their ability to effectively colonise the disturbed habitats of the culture steppe) and fall into the intermediate category of r- K strategists on the microscale as they colonise both the humus and litter fractions of the soil profile. However, the ability of H. purpurescens to colonise native vegetation on a wide scale indicates that this species could probably be classed as a flexible r-K strategist on the macroscale. Some r strategists can survive in even the most stable environments if they can adapt to the unpredictable changes in that environment (Matthews 1976), and the few recordings of H. sp. cf. engadinensis and H. gibbosa in native vegetation further suggest that other Hypogastrura species have the ability to adapt to more stable environments which contain a high proportion of K species.

In disturbed habitats of the Solomon islands, Greenslade and Greenslade (1980) found an increase of r selected opportunistic isotomids. Fjellberg (1985) discussed the negative effects of such a faunal shift on more specialised K selected species, noting that such species were stenotopic, rare and needing special protection.

The observation of H. denticulata, H. sp. cf. engadinensis, H. vernalis and H. viatica swarming or aggregating in large numbers is a phenomenon that is probably characteristic of many species in the genus, their ability to build up in large numbers probably being associated partly with their apparent distastefulness to predators (Bellinger 1960). Overseas, swarms or large aggregations have been recorded for H. viatica (Brown 1921; Turk 1932) and H. purpurescens (Brown 1921).

Reports of large aggregations of Hypogastruridae in the Tasmanian culture steppe have often been associated with enquiries as to their pest status, and species have frequently appeared in published lists of injurious Collembola (Collinge 1909; Theobald 1911; Mills 1930; Folsom 1933; Womersley 1939; Paclt 1956). However, the lack of firm evidence of

primary plant damage from this study suggests that many of these old records listing Hypogastruridae as pests of plants are probably incorrect. The available evidence suggesting these species are mainly secondary feeders, i.e. they feed mainly on dead and decaying plant material or the micro-organisms associated with the breakdown process (bacteria and fungi).

In cases where primary damage has been reported it is possible by the time damage to plant material has been noticed, the primary causes of the damage (animal or microbial) may have been masked by the secondary processes of decay which are often associated with the aggregation of large numbers of Hypogastrura spp. feeding on decaying plant material, damage exudates or on associated micro-organisms. There is also evidence that the presence of exudates from damage plant material such as sugars (Macnamara 1924) and alcohols (Greenslade and Greenslade 1971) may attract and stimulate feeding in Hypogastruridae. Greenslade and Greenslade (1983) concluded that feeding in Hypogastruridae is very variable between species and includes algae, fungal hyphae and spores, bacteria associated with vertebrate and invertebrate carrion, autolysing fungi and dung. Actual feeding studies in culture on H. manubrialis (Vail 1965) showed the species to have a gregarious habit when abundant food was available and although a general feeder it preferred yeasts and moulds. The commercial mushroom (Agaricus campestris) was also an acceptable food. Strebel (1932) found that H. purpurescens was also a general feeder and would eat a variety of foods in culture, high in either protein (cheese), fat (butter) or carbohydrate (potato). He also found that macerated foods were more attractive. Ripper (1930) reported that H. manubrialis was a general feeder on fresh and decaying organic matter and was also able to culture species on mushrooms, adding that the species could be a serious pest of mushroom cultures. Paclt (1956) lists Hypogastrura armata (Nicolet) as being an important worldwide pest of mushroom cultures where conditions can enable the breeding of millions of individuals (Thomas 1929). H. denticulata, H. manubrialis, H. purpurescens and H. vernalis have all been identified as damaging mushroom cultures in mainland Australia (Greenslade pers. comm.) although there are no published records from Tasmania. Clift (1983) states that the species were pests of the commercial mushroom Agaricus bisporus when they were grown in outdoor ridge beds but are now of little importance since the advent of purpose-built houses, pasteurization of compost and the use of heat in casing. It is probable that mushroom cultures are the only authentic situation in which hypogastrurid species have been pests of agricultural crops, other than this, however, their activity within the culture steppe can be regarded as beneficial.

CHAPTER 13

ADDITIONAL RECORDS, SPECIES LIST AND KEY TO COLLEMBOLA FROM THE TASMANIAN CULTURE STEPPE

INTRODUCTION

This chapter details and discusses additional records of Collembola from the Tasmanian culture steppe including species entering buildings. A final list of all species identified during the entire study is presented and keys given to their identification.

MATERIALS AND METHODS

(i) Collection

Collection methods together with clearing and mounting procedures are detailed in Chapter 2.

(ii) Species identification

The designation of an actual species name to Collembola at the commencement of this work was in many cases difficult because the only published keys available on the Australian fauna were by Womersley (1939). Because of the advances made in collembolan taxonomy since Womersley's time, most of his work is considerably outdated. Many of the names have been changed and the descriptions are not really full enough for confident determination and lack clarity on certain points. Further, most of his descriptions are based on morphological characters that can only be seen on mounted specimens. For this work, population counts of the species collected at monitored sites and during surveys required a more rapid method of identification. Following examination of large numbers of specimens, it became obvious that identification to generic level and in many cases to species or species groups was possible by examination of unmounted specimens in alcohol and the use of colour and morphological characters that could be seen with the aid of a dissecting microscope at low magnifications (ca x 25 to x 50). Each species collected during surveys or from monitored sites was therefore initially assigned a code until identification was confirmed. Actual species identification was achieved using overseas keys of Stach (1947, 1949, 1954, 1956), Maynard (1951), Murphy (1960), Gizin (1960), Salmon (1941), Richards (1968), Ellis (1974a), Najt and Massoud (1974), Christiansen and Bellinger (1980a, 1980b, 1980c, 1981), Fjellberg (1980) and by collaboration with P. Greenslade who also had access to Womersley's type material lodged at the South Australian Museum, Adelaide.

Colour characters were generally found to be a reliable means of distinguishing some species, but such characters were found to vary not only interspecifically but intraspecifically particularly in the Sminthuridae (eg Sminthurinus and Katianna), the variations probably being caused mainly by environmental factors, temperature being particularly important (Rapoport 1969; Walters 1964). Although it was possible to easily distinguish many species by their colour variations, other characters observable only by examination of mounted specimens were also used. For example, one green colour form of the undescribed Katianna sp.1 that occurs in pasture (Chapter 8) is easily confused with S. viridis, and mounted specimens were occasionally used to observe the

distinguishing characters. Similarly, species of Hypogastruridae, species groups of Onychiuridae and some species of Isotomidae could only be identified by examination of slide mounts.

A combination of colour and other characters that were used to separate species of the Tasmanian culture steppe is presented in a key, together with illustrations at the end of this chapter.

RESULTS

Table 13.1 lists the additional records of Collembola identified in samples taken from lawns, litter from home gardens, introduced grasses along roadsides and from a few suburban localities. Table 13.2 lists the species that have been identified entering buildings. Table 13.3 gives the final list of all species recorded from the Tasmanian culture steppe together with a summary of their worldwide distribution, preferred microhabitats and pest status.

DISCUSSION

The hypogasturid X. welchi, the entomobryids Lepidocytus sp., cf. Willowsia sp., E. atrocincta and the isotomid P. filifera (reported as a pest of earth-worm cultures in Britain by Greenslade and Fletcher 1986), although not recorded during the more detailed surveys of pastures and field crops, were all collected in disturbed habitats near population centers. Prior to this work, none of these species had been previosly recorded in Tasmania. The sminthurid, D. pallipes, has a wide distribution in Europe (Salmon 1964). Ellis (1974b) recorded the species from dwarf shrubs (mainly Vaccinium) in deciduous woods in the Netherlands and cites Gisin (1948) as recording it as an inhabitant of steppe-like grasslands. The records in Table 13.1 are the first for Australia. The collection dates suggest that its main period of activity is summer, which is similar to that recorded in Europe (Lubbock 1868). The cosmopolitan T. vulgaris recorded by Womersley (1939) from Hobart, and identified during this study from previously collected material (Table 13.1) has not been collected since. It is possible that the species was a direct introduction from Europe and may be confined to urban Hobart. The other species recorded in lawns were also common in pastures and/or field crops and it is probable that most species common on agricultural land may also occur in suburban environments, as is the case with the Hypogastrura species discussed in Chapter 12.

Because sampling methods used were mainly for the collection of surface-active species, few euedaphics were collected. However, the native C. caecus that was extracted from litter and surface soil from a pine plantation is probably a common inhabitant of soil in Tasmania. In addition, the cosmopolitan species Isotomodes productus and Isotomiella minor that were collected from soil in pastures are probably quite widespread. Both C. caecus and I. productus were among the most common euedaphics extracted from soil cores taken from temperate pasture at

Table 13.1 Miscellaneous records of Collembola recorded in the Tasmanian culture steppe.

Species	Date recorded	Locality	Situation
Sminthuridae			
K. australis	3.6.71	Grove	Leaf litter (apple orchard)
	5.9.76	Mt Nelson	Lawn
K. mucina	5.1.77 8.1.77	Mt Nelson (Olinda Grove)	Native and introduced grasses, roadside
K. oceanica var. *schoetti*	18.9.75	Preston-Central Castra Road	Ground litter ex *Pinus radiata*
	30.7.76	Mt Nelson	Leaf litter ex *Cotoneaster* (home garden)
	5.1.77	Mt Nelson (Olinda Grove)	Native and introduced grasses, roadside
K. sp. 1	28.4.84	Mt Nelson	Lawn
	21.4.89	Mt Nelson	Lawn
S. elegans	28.2.76	West Hobart	Lawn
	9.3.89) 14.3.89)	New Town	Lawn
D. pallipes	31.1.77) 3.2.77)	South Hobart (Old Farm Rd)	Introduced grasses, roadside
	14.3.78	South Hobart (Waterworks Rd)	Introduced grasses, roadside
D. sulphureus mediteranneus	11.2.76	Lauderdale	Introduced grasses roadside
	30.1.77	Mt Nelson (Olinda Grove)	Native and introduced grasses, roadside
	31.1.77	South Hobart (Old Farm Rd)	Introduced grasses roadside
	14.3.78	South Hobart (Waterworks Rd)	Introduced grasses, roadside

Table 13.1 (cont.) Miscellaneous records of Collembola recorded in the Tasmanian culture steppe.

Species	Date recorded	Locality	Situation
B. hortensis	19.12.77	Flowerdale	Introduced grasses near edge of pasture
	18.1.77	Oatlands	Introduced grasses, roadside
	31.1.77) 3.2.77)	Sth Hobart (Old Farm Road)	Introduced grasses, roadside
	28.4.84	Mt Nelson	Lawn
Entomobryidae			
E. atrocincta	3.2.76 30.8.76	Mt Nelson	Leaf litter ex *Cotoneaster* (home garden)
E. marginata	28.4.84	Mt Nelson	Lawn
	9.3.89	New Town	Lawn
E. multifasciata	12.6.65	Moonah	Home garden
	3.6.71	Grove	Leaf litter (apple orchard)
	15.9.75	nr Quamby Bluff (Lake Highway)	Introduced grasses, roadside (Lake Highway)
	19.9.75	Ross	Introduced grasses, roadside
	19.9.75	Deloraine	Introduced grasses, roadside
	.10.75	Low Head	Introduced grasses, near beach
	3.2.76	Mt Nelson	Leaf litter ex *Cotoneaster* (home garden)
	2.6.76	Plenty	On blackcurrant bushes
	5.7.76	Grove	Under cardboard around butt of apple tree
E. unostrigata	12.11.65	Moonah	Large numbers in home garden

Table 13.1 (cont.) Miscellaneous records of Collembola recorded in the Tasmanian culture steppe.

Species	Date recorded	Locality	Situation
E. unostrigata	29.4.84 9.3.89	New Town	Lawn
cf. *Willowsia* sp.	.2.81	Launceston	Large numbers in home garden
Isotomidae			
P. filifera	26.2.76	Devonport	Identified together with large numbers of *Xenylla* on council grounds
C. thermophilus	19.9.75	Ross	Litter, introduced grasses, roadside
	17.9.75	Arthur River	Litter ex native and introduced grasses
I. palustris	19.9.75	Deloraine	Introduced grasses, roadside
	28.4.84	Mt Nelson	Lawn
	26.6.79	Latrobe	On oil poppy seedlings in glasshouse
I. notabilis	18.9.75	Preston - Central Castra rd.	Ground litter ex *Pinus radiata*
	19.9.75	Ross	Litter ex introduced grasses
Hypogastruridae			
Triacanthella sp.	1.12.77	Hobart (Battery Point)	Large numbers in heavily composted garden soil
	11.4.78	Hobart (Mt Stuart)	Large numbers in heavily composted garden soil
Xenylla welchi Folsom	26.2.76	Devonport	Large numbers aggregating on council grounds
	9.5.77	Launceston	Large numbers in horse manure

Table 13.1 (cont.) Miscellaneous records of Collembola recorded in the Tasmanian culture steppe.

Species	Date recorded	Locality	Situation
Neanuridae			
B. platensis	1.5.51	Kempton	Mushrooms
	18.5.84	New Town	Lawn
	28.4.84	New Town	Lawn
	9.3.89	Mt Nelson	Lawn

Table 13.2 Species of Collembola recorded entering buildings in Tasmania.

Species	Date recorded	Locality	Reported Situation
Entomobryidae			
E. unostrigata	22.1.76	Launceston	Large numbers around damp areas inside monastery
	27.1.76	Latrobe	Large numbers entering hall
	9.3.78	Jetsonville	Large numbers in and around farmhouse
	3.2.81	Scottsdale	Large numbers inside hospital
	10.2.81	Legana	Large numbers inside house (bathroom)
	15.3.83	Lauderdale	Large numbers inside house
	2.3.84	Launceston	Large numbers on floor of factory
	15.3.84	New Norfolk*	Large numbers in and around house (bathroom sink)
	4.1.89	Old Beach	Large numbers inside house (around sink)
	7.1.89	Richmond	Large numbers inside house (bathroom)
E. marginata) *E. multifasciata*)	3.1.89	Berriedale	Large numbers inside house
Lepidocyrtus sp.2	1.3.82	Glenorchy	Large numbers entering house
Isotomidae			
I. palustris	30.4.79	Launceston	Large numbers invading porch and windowsills.
I. tigrina	8.12.83	Devonport	Large numbers invading back porch and wall of house
Hypogastruridae			
H vernalis	25.5.87	Georgetown	Large numbers entering factory

* Resident reported being bitten by this species with no apparent side effects

Table 13.3 A summary of the Collembola identified in the Tasmanian culture steppe giving geographical distribution, microhabitat preference, collection records and damage assessment category.

Species	Geographical distribution a	Preferred microhabitat b	Collection records c	Damage assessment d
Dicyrtomidae				
cf. Dicyrtomina sp.1	?	L	P	4
Sminthuridae				
Sphaeridia pumilis (Krausbauer grp)	C	H,L	P	4
Jeannenotia stachi australiensis Betsch and Massoud	N?	H,L	P,FC	4
Sminthurides sp.1	C	L	P	4
Katianna australis Womersley	N	L,V	P,FC,L,O	2
Katianna mucina Womersley	N	L,V	P,RG	2
* Katianna sp. cf. obscura (Womersley)	N	L,V	P	2
Katianna ornata Womersley	N	L,V	P	2
Katianna sp. cf. pescotti Womersley	N	L,V	P	2
Katianna oceanica var schoetti Womersley	N	L,V	P,HG,PR	2
Katianna sp.1	N	L,V	P,L	2
Sminthurinus elegans (Fitch)	C	L	P,L	4
* Sminthurinus mime Boerner	C	L	P	4
* Sminthurinus tuberculatus Delamare and Massoud	N?	L	P	4
Sminthurinus sp. 1	?	L	P	4
Deuterosminthurus pallipes (Bourlet)	C	L,V	RG	4

Table 13.3 A summary of the Collembola identified in the Tasmanian culture steppe giving geographical distribution, microhabitat preference, collection records and damage assessment category.

(cont.)

Species	Geographical distribution a	Preferred microhabitat b	Collection records c	Damage assessment d
* Deuterosminthurus sulphureus mediterraneus Ellis	C	L,V	P,RC,RG	4
Prorastriopes quinquefasciatus (Krausbauer)	C	L,C	P,FC	3
Bourletiella hortensis (Fitch)	C	L,V	P,FC	1
* Bourletiella viridescens Stach	C	L,V	P,FC,RG	1
Corynephoria sp.1	N	L,V	P	4
Sminthurus viridis (L.)	C	L,V	P,FC	1
Entomobryidae				
Australotomurus echidnus Womersley	N	L,V	P	4
* Entomobrya atrocincta Schoett	C	L	HG	4
Entomobrya sp. cf. lanuginosa (Nicolet)	C	L,V	P	4
Entomobrya marginata (Tullberg)	C	L	P,FC,L,B	4
Entomobrya multifasciata (Tullberg)	C	L,V	P,FC,HG,L,B,O,RG,BL	3
Entomobrya unostrigata Stach	C	L,V	P,FC,L,B,HG	2
Lepidocyrtoides spp.	?	L,V	P	4
Lepidocyrtus sp.1	?	L	P	4
Lepidocyrtus sp.2	?	L	HG,B	4
cf. Willowsia sp.1	?	L	HG	4
Pseudosinella sp. nr. alba (Packard)	C	S	P	4

Table 13.3 A summary of the Collembola identified in the Tasmanian culture steppe giving geographical distribution, microhabitat preference, collection records and damage assessment category.

(cont.)

Species	Geographical distribution a	Preferred microhabitat b	Collection records c	Damage assessment d
Isotomidae				
* Folsomia candida	C	S	BU(HG,NU),IP	1
* Cryptopygus caecus Wahlgren	N	S	PR	4
Cryptopygus thermophilus (Axelson)	C	H,L	P,FC	4
Proisotoma filifera Denis	C	H,L	L	4
Proisotoma minuta (Tulberg)	C	H,L	BU(NU)	4
Isotomurus palustris (Mueller) group	C	H,L	P,FC,HG,L,B,GL	3
Isotoma notabilis Schaeffer	C	H	P	4
* Isotoma tigrina (Nicolet)	C	H,L	P,FC	4
Isotomiella minor (Schaeffer)	C	S	P	4
Isotomodes productus (Axelson)	C	S	P	4
Onychiuridae				
Onychiurus sp. ambulans (L.) group	C	S	HG	1
Onychiurus sp. armatus (Tullberg) group	C	S	P,FC,HG	1
Onychiurus sp. fimetarius (L.) group	C	S	P,FC,HG	1
Tullbergia sp. 1	?	S	P	4
Dinaphorura sp. 1	?	S	FC	4
Hypogastruridae				
* Hyposastrura (Ceratophysella) denticulata (Bagnall)	C	H,L	P,FC,HG,NU,SW	3^{+}

Table 13.3 A summary of the Collembola identified in the Tasmanian culture steppe giving geographical distribution, microhabitat preference, collection records and damage assessment category.

(cont.)

Species	Geographical distribution a	Preferred microhabitat b	Collection records c	Damage assessment d
Hypogastrura (C.) sp. cf. engadinensis Gisin	C	H,L		3^+
Hypogastrura (C.) gibbosa (Bagnall)	C	H,L		3
Hypogastrura (Hypogastrura) assimilis (Krausbauer)	C	H,L		3
Hypogastrura (H.) manubrialis (Tullberg)	C	H,L		3^+
Hypogastrura (H.) purpurescens (Lubbock)	C	H,L		3^+
Hypogastrura (H.) vernalis (Carl)	C	H,L		3^+
Hypogastrura (H.) viatica (Tullberg)	C	H,L		3
Triacanthella spp.	?	H,L	P,HG,SW	3
Xenylla welchi Folsom	C	H,L	L,D,SW	4
Xenylla sp. 1	?	H,L	FC	4
Neanuridae				
* Brachystomella platensis Naj and Massoud	C	H,L	P,FC,HG,L,MU	4
Neanura muscorum (Templeton)	C	H,L	P	4

a Geographical distribution : C = introduced and probably cosmopolitan, occurring on at least three other continents; N = native to Australia

b Preferred microhabitat (active stages only) : S = soil ; H = humus, surface soil ; L = soil suface and litter layer ; V = vegetation

c Collection records : P = pasture ; FC = field crops ; HG = home gardens ; L = lawns ; B = buildings ; O = orchards ; RG = introduced grasses along roadsides or in ungrazed areas particularly roadsides ; PR = Pinus radiata plantations ; BL = blackcurrant bushes ; GL = glass houses ; D = dung ; MU = mushrooms ; BU = bulbs ; NU = nurseries ; IP = indoor plants ; SW = may occur in aggregates or swarms.

d Damage assessment : 1 = primary damage sometimes needing control measures, seedling crops particularly susceptible ; 2 = primary damage rare, secondary food sources preferred, no confirmed records of damage to crops or pastures in Tasmania ; 3 = no primary damage, secondary feeding only; 4 = no data available on feeding habits, but secondary food sources probably preferred.

* Species included in Womersley's (1939) list of injurious Collembola but were recorded under a different name (Greenslade in press (b)): Katianna obscura as Parakatianna obscura, Womersley; Sminthurinus mime as Sminthurinus terrestris Womersley; Sminthurinus tuberculatus as Sminthurinus aureus (Lubbock) and S. igniceps (Reuter); Deuterosminthurus sulphureus mediterraneus as Deutersosminthurus bicinctus var. repandus (Agren); Bourletiella viridescens (as Bourletiella arvalis (Fitch); Entomobrya atrocincta as Entomobrya clitellaria Guthrie; Folsomia candida as Folsomia fimetaria (L.); Cryptopygus caecus as Folsomia fimetariodes (Axelson); Isotoma tigrina as Isotoma olivacea (Tullberg); Hypogastrura denticulata as Hypogastrua armata (Nicolet); Brachystomella platensis as Brachystomella parvula (Schaeffer).

\+ On the mainland, these species of Hypogastrura were often recorded as primary pests of mushroom beds (Greenslade in press(a)) before the advent of proper sterilization procedures (Clift 1983). There are no records of these species damaging mushrooms in Tasmania.

Note:
Immature specimens of the Sminthurid Rastriopes dromedarius (Womersley), were collected from carrots in December 1926 but the species has not since been collected from agricultural land despite attempts to do so at the type locality during this study; it is therefore not included in this list. Although more immature specimens were collected by Greenslade (pers. comm.) in February 1986 by sweeping coastal heath vegetation, nothing else is known about the phenology, distribution and habits of the species which appears to be endemic.

Armadale (NSW), with I. minor also identified in smaller numbers (King et al 1976).

Examination of Table 13.1 shows that species usually recorded entering houses are entomobryids during summer, particularly E. unostrigata. Such occurrences were often recorded if the dwellings were situated close to suitable habitats such as long grass. In California, Scott (1964) reports that migration of E. unostrigata into houses is quite common especially where housing developments adjoin waste land or agricultural land. E. multifasciata, E. marginata and E. unostrigata appear less susceptible to dry conditions than other Arthropleona (Davies 1929; Vannier 1973) and in Tasmania these species are active in pastures and in lawns during summer months (the effect of low humidity in relation to ecological distribution was discussed in Chapter 8). Mari Mutt (1978) reported a swarm of E. unostrigata in Illinois (USA) at a time when no rains were reported in the area and relative humidities were low. Perhaps the aggregation was part of a survival mechanism triggered by the sub-optimal humidity. Thus, if conditions get too dry, swarms may actively seek out moister conditions and create a nuisance by migrating into buildings. This would explain their frequently reported occurrence around baths and sinks (Table 13.2), a phenomenon also recorded by Scott (1964, 1966) and Ebeling (1975). The three other species recorded entering buildings, I. palustris, I. tigrina and H. vernalis, have higher moisture requirements than entomobryids and would not be expected to survive indoors unless conditions inside are damp. I. palustris and H vernalis were recorded entering houses in late autumn. Perhaps a brief dry spell following a period of peak autumn activity may have been the cause of the migration.

On the mainland, native entomobryid species belonging to the genera Lepidocyrtoides, Lepidocyrtus and Willowsia are also occasionally recorded indoors; the introduced species E. atrocincta and Seira domestica (Nicolet) have also been known to persist in buildings in small numbers, although their occurrence in buildings does not appear to be determined by weather (Greenslade pers. comm.). Although S. domestica has not been recorded from Tasmania, the occurrence of a Lepidocyrtus sp., cf. Willowsia sp. and E. atrocincta in home gardens suggest these could invade dwellings from time to time.

The instance where a woman reported being bitten by E. unostrigata (Table 13.2 compares with records by Pescott (1942) of E. multifasciata and E. unostrigata causing skin irritations in humans. Pescott discussed the possibility of the setae on these species being the cause of the irritations, however, he concluded it was possible the species may have actually bitten their subjects. There are few other records in the literature of Collembola biting man and they have never been incriminated with the transmission of human disease. In America, Orchescella albosa Guthrie which does not occur in Australia was reported in one instance as infecting heads and pubic areas without causing any dermatitis (Scott

1962), and the cosmopolitan E. nivalis was recorded as the cause of an allergic skin reaction in man (Scott 1966). Scott (op. cit) expressed doubts as to whether Collembola would actually bite as investigations usually revealed that skin reactions could be attributed to other causes such as crushing on the skin, which may cause a localised allergic response, and hopping on the skin which may cause itching. However, Lee (1975) cites an instance where S. viridis was reported to have bitten a man but with apparently no effect other than a light prick.

Prior to this study only about 16 of the 61 species (or species groups) from the 6 families listed in Table 13.3 had been previously recorded from Tasmania. Of the 61 listed, 39 are introduced and probably cosmopolitan, with at least 10 (or probably 12 species) being native. Of the cosmopolitan species, the largest genus is Hypogastrura (8 species) followed by Entomobrya (5 species). Most of the natives are epigaeic Katianna (7 species). Obviously the geographical distribution of 10 unidentified species belonging to non-native genera cannot be classified.

Although Neanuridae are well represented by many native species in Tasmania (Ireson unpubl. data) none of these were identified in the culture steppe, the only representatives being the cosmopolitan species B. platensis (which was widespread) and N. muscorum. This latter species is common in native vegetation in Tasmania, particularly amongst litter in wet forests (Ireson unpubl. data), however, it is rare in the culture steppe. King et al (1976) recorded it in small numbers from sown perennial pastures in Armidale (NSW) and it has only been recorded in the Tasmanian culture steppe in one instance from pasture (see Chapter 8, Fig. 8.44). P. quinquefasciatus and D. pallipes were the only species identified that have not been recorded on the mainland.

Damage assessment categories in Table 13.3 are based on observations reported in Chapters 9, 10 and 12. Only 3 epigaeics (S. viridis, B. hortensis and B. viridescens) and 4 euedaphics (F. candida and the 3 Onychiurus species groups) are recorded as causing significant primary damage necessitating the possible use of control measures. E. unostrigata was found to damage cotton seedlings in culture but was placed in category 2 as cotton is not grown in Tasmania and there are no other records of damage by this species to other plants here (Chapter 9).

KEY TO GENERA AND SPECIES OF COLLEMBOLA IDENTIFIED IN THE TASMANIAN CULTURE STEPPE

1. Body globular; three thoracic and anterior abdominal segments (1-4) fused dorsally into one mass (greater abdomen); abdominal segments 5 and 6 usually separate; furcula always well developed (Fig. 13.1) 2

   Body elongate; thoracic and abdominal segments separate; abdominal segments 5 and 6 sometimes fused; furcula well developed, rudimentary or sometimes absent (Fig. 13.1) 20

2. Antennae 4 reduced, less than one half the length of antennae 3 and without annulations; antennae elbowed between second and third segments (Fig 13.2); 2 thin parallel, maroon longitudinal stripes anteriorly on mid-dorsum of greater abdomen; prominent rectangular dark patch mid-dorsally on posterior abdomen..... .....cf. Dicyrtomina sp.(Fig.13.25)[A]

   Antennae 4 not reduced, more than one half the length of antennae 3, with or without annulations; antennae elbowed between third and fourth segments; colour patterns not as above.....3

3. Antennae 4 simple, without annulations (Fig. 13.3) dorsum of head without erect, spine-like setae.....4

   Antennae 4 annulated (Fig. 13.4); dorsum of head with or without erect, spine-like setae.....7

4. Dorsal and lateral parts of body completely black; head with light (white) strip or spot of pigment on inner margin of each eye patch.....5

   Dorsal and lateral parts of body usually with stripes or bands; if black, head always with paler areas as well as white spots on inner margins of each eye patch.....6

5. Legs, furcula and antennal segments 2, 3 and 4 distinctly white; adults ⩾ 1mm in length..... .....Sminthurinus mime Boerner (Figs 13.26, 13.27)

   Legs and furcula partly black; adult smaller < 1mm in length ....Sminthurinus tuberculatus Delamare and Massoud (Fig. 13.28)

6. Black with irregular white stripe laterally, sometimes broken by strips of black pigment; white blotch on inner margin of each eye patch; thin white continuous band extending entire distance between antennal bases at front; ventral surface including legs and furcula with pale whitish pigment often with a purplish tinge.....

.....Sminthurinus sp.1 (Fig. 13.29)[B]

Four broad irregular black longitudinal stripes on abdomen laterally on white or yellow background, a fifth narrower mid-dorsal stripe sometimes present; black blotch usually present centrally between antennal bases, flanked by patches of lighter pigment either side around inner margins of antennae (occasionally dark forms occur) ..... Sminthurinus elegans (Fitch)(Figs 13.30, 13.31)

7. Dorsum of head without erect, spine-like setae.....8

Dorsum of head with heavy, erect spine-like setae (Fig.13.5) 18

8. Distinct colour pattern of five prominent white bands across abdomen separated by broad dark bands.....
.....Prorastriopes quinquefasciatus (Krausbauer) (Fig. 13.32)

Pigment colours usually more uniform and diffuse (pink, blue, purple, green, orange, black, brown, yellow or yellow green) no bands or stripes although colour pigments sometimes (rarely) mottled 9

9. Small, adults < 1mm length uniformly pink, blue or purple, if darker then always tinged with blue or purple; strongly sexually dimorphic; females larger with completely spherical abdomen, antennae directed ventrally; males smaller with conspicuous antennae furnished with short spines, hooks or bulbs (Fig. 13.6) 10

Larger, adults > 1mm length; predominantly yellow, yellowish-green, orange, brownish, slate coloured or black (colour may vary within the same species).....12

10. Mucronal seta and tibiotarsal organ (t) absent (Figs 13.7, 13.10); adult female < 0.5mm length, adult male < 0.3mm length; furcula usually curved upwards in preserved (alcohol) specimens, following contour of body behind anus; antennae of males usually pointing forwards; antennal segments 2 and 3 each with a small spine .....Sphaeridia pumilis (Krausbauer) (Fig. 13.33)

Mucronal seta and tibiotarsal organ (t) present (Fig. 13.10); adults > 0.5mm in length; in preserved (alcohol) specimens, furcula usually lies parallel to line of body; antennae of male directed above head (Fig. 13.35); antennal segments 1 and 2 are broad and 2 and 3 furnished with strong spines.....11

11. Mucrona lamellae narrow, poorly developed (Fig. 13.8).....
Jeannenotia stachi australiensis Betsch and Massoud (Fig. 13.34, 13.35)

Mucronal lamellae large and complex (Fig. 13.9) .....
.....Sminthurides sp.1[C]

12. Large specimens, adults> 1.5mm in length; usually greenish-yellow, occasionally with black or brown mottles; dorsal setae on abdomen distinctly longer than claw or mucro.....
.....Sminthurus viridis (L.) (Fig. 13.36, 3.37)

Smaller specimens, adults < 1.5mm in length; orange-yellow, green, brown or black; dorsal abdominal setae shorter or equal to length of claw and mucro.....13

13. Convex abdomen; abdomen 6 with dorsal hooks distally in male (Fig. 13.11).....Bourletiella spp.....1

Saddle shaped abdomen; abdomen 6 without distal dorsal hooks in male..
.....14

14. Empodial appendage absent; 4 clavate tibiotarsal hairs present on all legs (Fig. 13.12).....Corynephoria spp.[D]

Empodial appendage present; 3 clavate tibiotarsal hairs or less present on legs (Fig. 13.13).....Deuterosminthurus spp.....15

15. Uniform orange-yellow colours.....
.....Deuterosminthurus sulphureus mediterraneus (Ellis) (Fig. 13.38)

Body colour darker, ranging from dark purple to black.....
.....Deuterosminthurus pallipes Boerner (Fig. 13.39)

16. Body usually blackish, dark bluish or slate coloured, if paler then oral half of head remains dark (slate coloured) and buff or rust coloured dorsally.....
.....B. hortensis (Fitch) (Fig. 13.40, 13.41)

Body usually orange or yellowish, if darker then oral half of head always pale .....B. viridescens Stach (Fig. 13.42, 13.43)

17. Pigment patterns dorsally and laterally on abdomen and head usually always present in stripes, bands or mottles of black, white, orange and yellow, rarely greenish.....18

Colours more uniform, usually yellow or green and if green then brown pigment pattern sometimes present.....19

18. Body mottled with black, green, yellow, brown and purple; 2 broad irregular, black longitudinal stripes anteriorly on mid-dorsum of greater abdomen, light yellowish pigment often visible between them;

dorsal area of posterior abdomen sometimes with 3 dark irregularly margined longitudinal bands of dark pigment, one situated mid-dorsally,the others on either side.....
.....Katianna australis Womersley (Figs 13.44, 13.45)

Black or grey markings on white or pale-yellowish background; 2 dark prominent transverse bands antero-dorsally on greater abdomen, narrowly interrupted medially; a third narrower, irregular and less prominent band anterior to these also interrupted medially; posterior abdomen often with T-shaped longitudinal dark stripe mid-dorsally and dark pigment stripes laterally .....
.....Katianna mucina Womersley (Fig. 13.46)

Body mottled, with orange, black and grey predominating, grey patches sometimes with purplish tinge, white pigment blotches present on some specimens; head with very prominent dark irregularly edged band around circumference below antennae; up to 5 pairs of conspicuous black spots situated medio-dorsally, distal pair in mid-abdominal region may extend laterally and posteriorly; pair of curved black stripes laterally on abdomen.....
.....Katianna sp. cf. obscura (Womersley) (Fig. 13.47)

Black and mauve markings on white background; single narrow dark longitudinal stripe running mid-dorsally, sometimes absent antero-distally and often broadening and irregular on posterior abdomen; posterior abdomen with up to 2 curved stripes with irregular margins on either side.....
.....Katianna ornata Womersley (Fig. 13.48)

Black, yellow or brownish pigment on predominantly white back-ground; yellow patch on vertex of head between ocelli; up to 4 narrowish dark transverse bands anteriorly on large abdomen, usually black but may be yellowish-brown and often posteriorly edged with yellow; a fifth band present which is sometimes joined posteriorly, although all bands may be widely interrupted medially; posterior abdomen with up to 3 usually black (may be yellowish-brown) longitudinal stripes dorsally, one situated mid-dorsally the others on either side.....
.....Katianna oceanica var. schoetti Womersley (Fig. 13.49)

19. Body a uniform pale yellow; arrow-shaped marking anteriorly on mid-dorsum of large abdomen, often faint and pointing posteriorly
.....Katianna sp. cf. pescotti Womersley (Fig. 13.50)

Green or yellow-green; some forms with a pair of light brown, broad stripes medio-dorsally, separated by a thin yellowish strip of pigment often visible even if brown pigment absent; brown stripes may become fused on posterior abdomen into a single narrower irregular stripe, sometimes more prominent than anterior paired stripes .....

.....Katianna sp.1 (Figs 13.51, 13.52)[E]

20.White; ocelli absent.....21

Coloured; ocelli present.....25

21.Furcula present.....22

Furcula absent; abdomen 4, 5 and 6 separate.....Onychiuridae (Figs 13.65, 13.66) (Key to genera and species groups on p. 339)

22.Abdomen 4, 5 and 6 fused.....Folsomia candida Willem (Fig. 13.64)

Abdomens 4 and 5 distinctly separate, abdomens 5 and 6 fused or not... 23

23.Abdomen 5 and 6 not fused but greatly shortened, curved downwards bearing long, straight setae; dens with single lateral seta distally (Fig. 13.14).....Isotomodes productus (Axelson)

Abdomens 5 and 6 fused and not downward curved; dens furnished with several setae anteriorly.....24

24.Antennae 4 with a group of thick, blunt sensory setae (Fig. 13.15); abdomen 5, 6 with long, serrated setae posteriorly and thickened sensory seta(s) on either side (Fig 13.16)..... .....Isotomiella minor Schaeffer

Abdomen 5, 6 without long serrated setae posteriorly; sensory setae on antennae 4 not as above.....Cryptopygus caecus Whalgren

25.Abdomen 4 much longer than other abdominal segments.....26

Abdomen 4 approximately equal in length to other abdominal segments.. 31

26.Body pigment either with or without patterns, scales present or absent 27

Body pigment usually not patterned; scales present, either black, brown, purplish or transparent, giving body an iridescent or shiny appearance.....29

27.Scales present; body pigment white except for small ocellar patches reduced to two black dots with only 2 ocelli in each patch..... .....Pseudosinella sp. nr. alba (Packard)

Scales absent; body pigment white or with other colours; ocelli not

reduced .....Entomobrya spp 28

28. Completely white, or white with greenish tinge except for antennal tip which is bluish grey, dark ocelli patches and dark spot between ocelli (Fig. 13.53) .....
.....Entomobrya sp. cf. lanuginosa (Nicolet)

All dorsal segments pigmented posteriorly with 8 or 9 dark red or purplish narrow bands on a white or yellowish background, pigment often reduced, abdomen IV posteriorly with a pair of triangular marks .....Entomobrya multifasciata (Tullberg) (Fig. 13.54)

Single, narrow, dark longitudinal line mid-dorsally, expanded to rectangular patch on abdomen III, narrow dark bands on posterior part of segments usually present.....
.....Entomobrya unostrigata Stach (Fig. 13.55)

Whole body dark or pale blue/grey/pink.....
.....Entomobrya marginata (Tullberg) (Fig. 13.56)

Body yellow with thorax II and abdomen I blue/black and thorax II white dorsally with dark margins to segments.....
.....Entomobrya atrocincta Scott (Fig 13.57)

29. Large specimens, adults > 2mm length; scales coloured, body with variable colours (dark-grey, purple, blue, black or brownish pigments) .....Lepidocyrtoides spp.[F]

Smaller specimens, adults < 2mm in length.....30

30. Scales ribbed, broad and all pointed (Fig. 13.17); blue patterns on white background.....cf.Willowsia sp.1[F]

Scales not ribbed, clear, variably shaped with some pointed, some rounded (Fig. 13.18); colours variable but uniform.....
.....Lepidocyrtus spp.[F] (Fig. 13.59)

31. Thorax I small but distinct and with setae; springing organ not or only just reaching abdomen II when flexed anteriorly, or absent.....38

Thorax I absent, no setae; springing organ easily reaching abdomen II when flexed forward or longer.....32

32. Adults > 1.5mm; distinct colour patterns present 33

Smaller, adults < 1.5mm; grey without pigment patterns.....34

33. Antennal segment I not sub-divided; pattern of longitudinal irregular purplish stripes or blotches on a lighter background, mid-dorsal stripe usually the most distinct .....Isotomurus palustris Mueller group (Fig. 13.58)[G]

Antennal segment I sub-divided into 2 parts; head, thorax and abdominal segments variably mottled with a dark brown and yellowish pigment (these colours may be dark purple and whitish in specimens stored in alcohol for long periods). Patterns, particularly on thoracic and anterior abdominal segments, may give the appearance of broken stripes; very thin mid-dorsal stripe often visible (much less pronounced than that described for I. palustris) on thoracic segments of some specimens extending from thorax to abdominal segment 1 and sometimes 2. Patterns vary and mottling sometimes less pronounced on posterior abdominal segments, the dark pigment colours being more uniform over entire segments. Dark brown and yellowish pigment (may be dark purple and whitish in stored alcohol specimens) on legs and furcula; dark pigment on sub-segments of antennae I but much lighter on antennal segments 2-4 .....
.....Australotomurus echidnus (Womersley) (Fig. 13.60)

34. Abdomen 5 and 6 fused; in preserved (alcohol) specimens, furcula often projected almost at right angles to body .....
.....Cryptopygus thermophilus (Axelson) (Fig. 13.61)

Abdomen 5 and 6 separate; in preserved (alcohol) specimens furcula usually projected at an angle > 90° from the body.....35

35. Manubrium with few anterior setae (< 15) (Fig. 13.19).....
Proisotoma spp.[H].....36

Manubrium with many anterior setae (Fig. 13.20).....37

36. Ocelli 6+6; mucro with 2 teeth; dens with 16-17 posterior setae and 2 anterior setae distally (Fig. 13.21).....Proisotoma filifera Denis

Ocelli 8+8; mucro with 3 teeth; dens with about 5-6 posterior and 5-6 anterior setae (Fig. 13.22) .....Proisotoma minuta (Tullberg)

37. Adults up to 1mm in length; 4 ocelli; mucro with 3 teeth (Fig. 13.23).....Isotoma notabilis Schaeffer

Adults larger, up 2mm in length; 8 ocelli; mucro with 4 teeth (Fig. 13.24).....Isotoma tigrina (Nicolet) (Fig. 13.62)

38. Spines present dorsally on abdomen 6; mandibles present .....Hypogastruridae 39

Dorsal spines absent; mandibles absent.....41

39.Three spines distally on abdomen 6, centre spine slightly more ventral; colour pink or white.....Triacanthella spp (Fig. 13.67)[I]

Two spines, either clearly visible, curved forward and longer than claw length or small, not clearly visible and shorter than claw length; colour variable, often dark purple or black, red or reddish brown.....40

40.Ocelli 8+8; post-antennal organ (PAO) present .....
.....Hypogastrura spp. (Fig. 13.68) (Key to species on pp. 342-343)

Ocelli 5+5 (or less) PAO absent.....Xenylla spp[J].....42

41.Abdomen 6 rounded in profile; colour usually pink .....
.....Brachystomella platensis Najt and Massoud (Fig. 13.69)

Abdomen 6 bilobed; colour greyish to dark blue.....
.....Neanura muscorum (Templeton) (Fig. 13.63)

A Placement of this species in Dicyrtomina is tentative pending revision of this genus. Womersley (1939) identified 3 species in Dicyrtomina, however, according to Greenslade (in press(b)) these may belong to a new genus as they possess certain characters inconsistent with Dicyrtomina

B Sminthurinus sp.1: species pending identification.

C Sminthurides sp.1: no furthur identification attempted pending revision of species within this genus.

D Corynephoria: 3 species have been collected in Tasmania (Greenslade and Ireson unpubl. data), two of which have not been described (Greenslade pers. comm.).

E Katianna sp.1: species not yet described.

F Lepidocyrtoides, Willowsia, Lepidocyrtus: a revision of species within these genera is required which include some native species, several of which are probably undescribed. No further identification is therefore attempted. Identification of Willowsia to genus is also tentative pending furthur examination of specimens.

G Cassagnau (1987) described five colour patterns in five populations of I. palustris from south-west France as the sub-species prasina, hortorum, palustris, maculata and catalana. It is therefore possible that a number of sub-species occur in Tasmania. Until more work is

done on the Tasmanian material, Isotomurus palustris Mueller is listed here as Isotomurus palustris Mueller group to include sub-species.

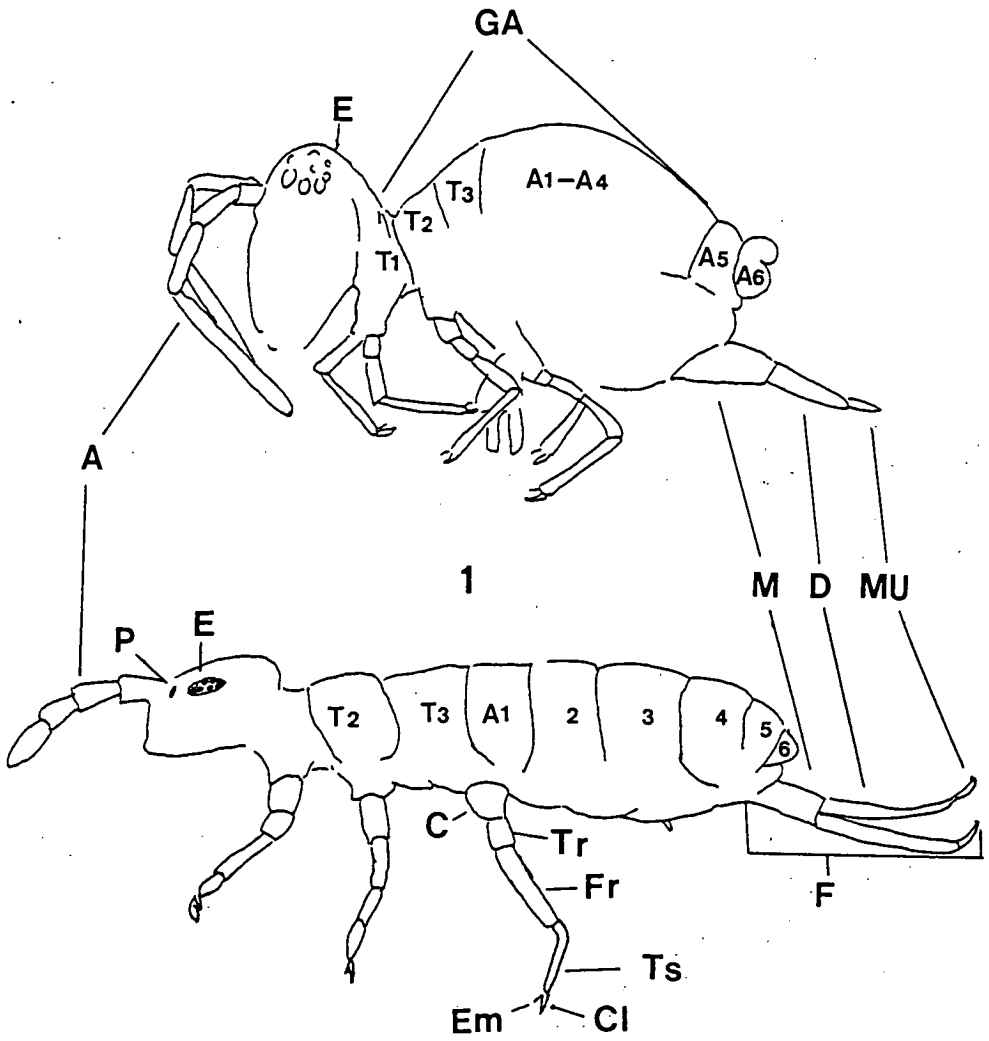
H Proisotoma: this is a large and complex genus with a wide distribution. Identification of the two species identified in the Tasmanian culture steppe (P. minuta and P. filifera) (Table 13.3) was made using the keys of Stach (1947) Christiansen and Bellinger (1980b) and Ellis (1970). It is probable that there are several other species in Tasmania probably within the culture steppe.

I Triacanthella: no attempt made at identification pending revision of species, several of which are undescribed.

J Xenylla: a key to the known Australian species is given by Gama and Greenslade (1981).

Fig. 13.1 Generalised diagram of globular collembolan (Symphypleona) (after Richards 1968) and elongate collembolan (Arthropleona): GA = greater abdomen (globular species); P = post-antennal organ; E = eyepatch; A = antenna; T1, T2, T3 = thoracic segments 1, 2 and 3; A1 - A6 = abdominal segments 1 - 6; M = manubrium; D = dens; MU = mucro; F = furcula; C = coxa; Tr = trochanter; Fr = Femur; Ts = Tibiotarsus; Cl = claw; Em = empodial appendage.

Fig. 13.2-13.4 Generalised diagrams of antennae: (2) elbowing between segments 2 and 3 and reduced antenna 4 (Dicyrtomina); (3) antenna elbowed between segments 3 and 4, segment 4 without annulations (Sminthurinus); (4) antenna elbowed between segments 3 and 4, segment 4 annulated.



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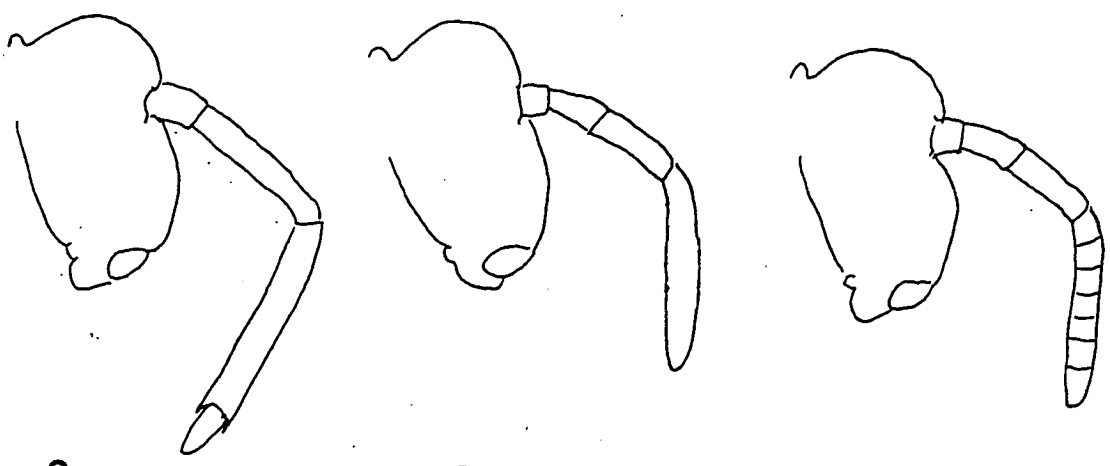


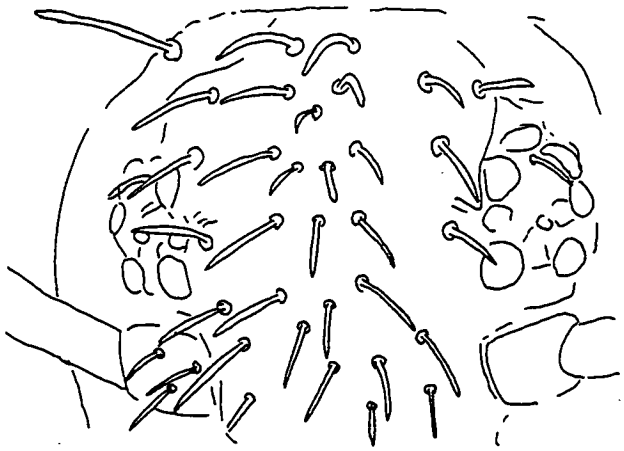
2 3 4

Fig. 13.5 Spine-like setae on vertex of head (Katianna spp.).

Fig. 13.6 Male antenna of J. stachi australiensis showing short spines, hooks and bulbs (after Betsch and Massoud 1970).

Fig. 13.7-13.9 Mucrones : (7) S. pumilis (after Christiansen and Bellinger 1981); (8) J. stachi australiensis (after Betsch and Massoud 1970); (9) Sminthurides sp.1.

Fig. 13.10 Tibiotarsal organ of J. stachi australiensis.



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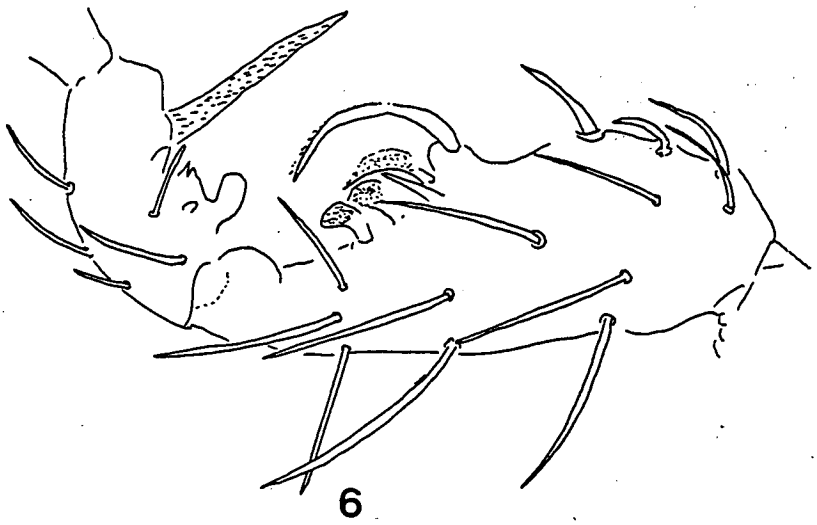

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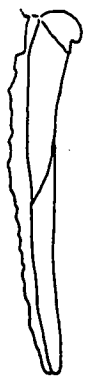

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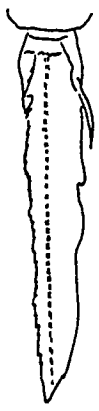

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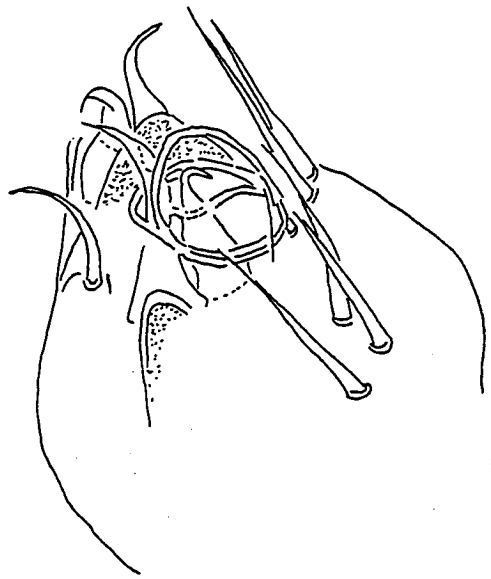
Fig. 13.11 Abdomen 6 of male B. hortensis showing distal dorsal hooks (after Fjellberg 1980).

Fig. 13.12 Empodium of Corynephoria sp.1 (4 clavate tibiotarsal hairs, empodial appendage absent).

Fig. 13.13 Empodium of Deuterosminthurus (3 clavate tibiotarsal hairs, empodial appendage present).



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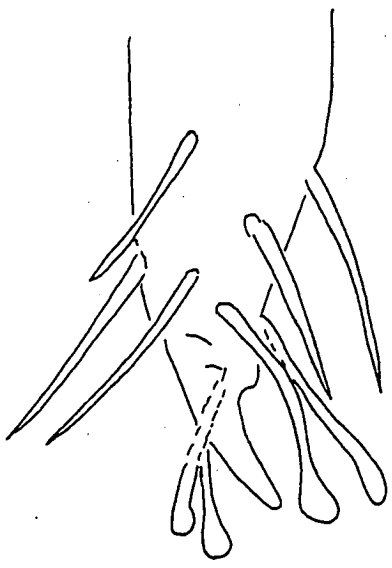

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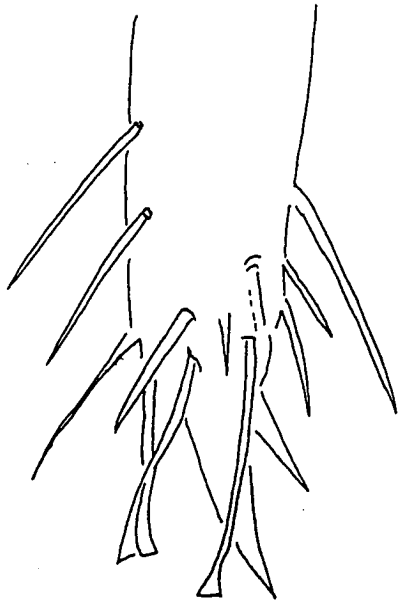

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Fig. 13.14 Dens chaetotaxy of Isotomodes productus (after Fjellberg 1980).

Fig. 13.15 Antenna 4 of Isotomiella minor showing thick, blunt sensory setae (after Fjellberg 1980).

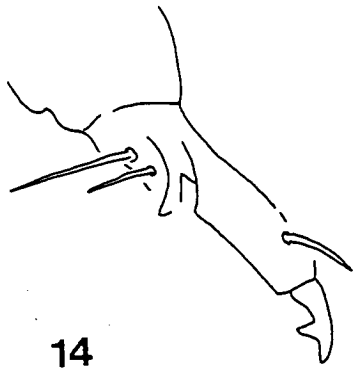
Fig. 13.16 Abdomens 5 and 6 of I. minor fused, with long serrated setae posteriorly and thick sensory seta laterally (s = sensory seta) (after Fjellberg 1980).

Fig. 13.17 Scales of cf. Willowsia sp.1.

Fig. 13.18 Scales of Lepidocyrtus sp.

Fig. 13.19 Proisotoma sp. showing anterior manubrial chaetotaxy (after Fjellberg 1980).

Fig. 13.20 Anterior manubrial chaetotaxy of Isotoma tigrina.



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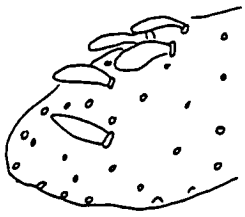

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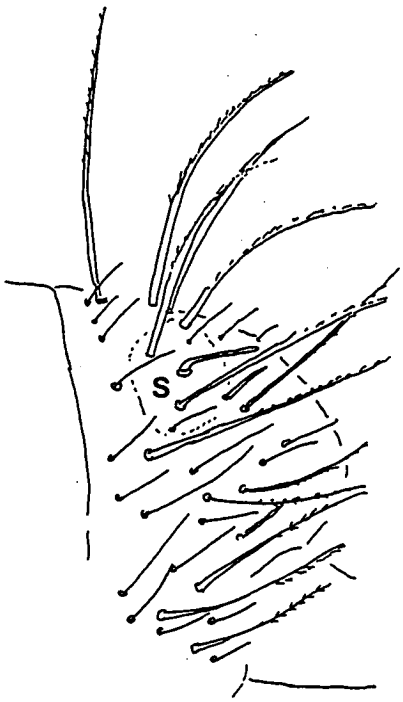

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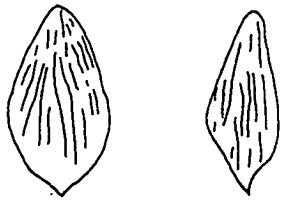

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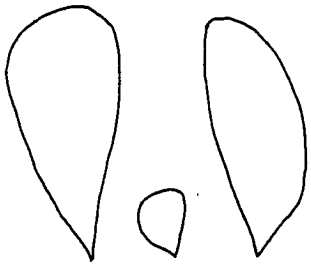

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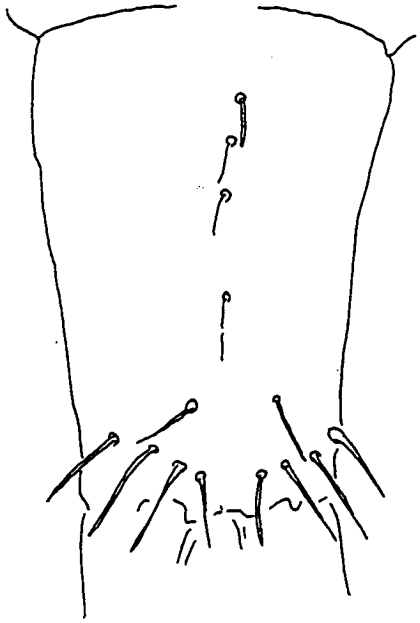

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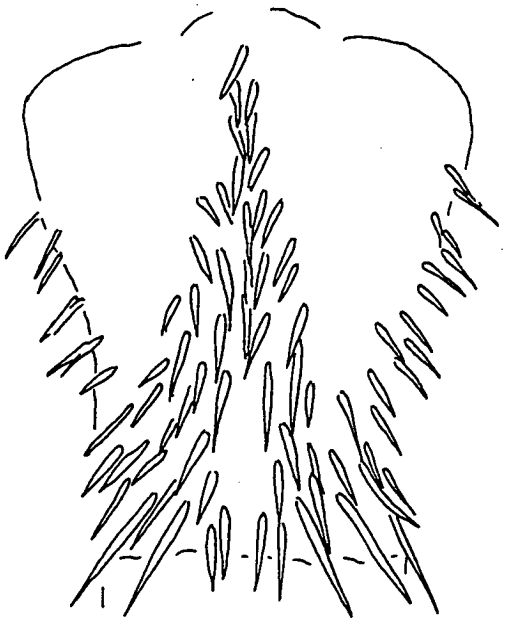

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Fig. 13.21 Mucro and dens of Proistoma filifera (lateral view) (after Ellis 1970).

Fig. 13.22 Mucro and dens of P. minuta (posterior view) (after Fjellberg 1980).

Fig. 13.23 Mucro of Isotoma notabilis (after Fjellberg 1980).

Fig. 13.24 Mucro of I. tigrina (after Fjellberg 1980).

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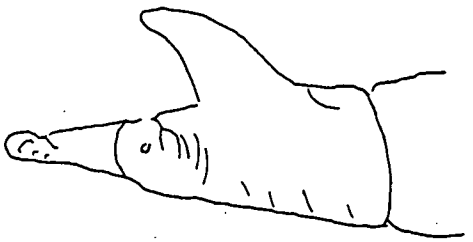

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Figs. 13.25-13.39 Colour photographs of Collembola identified in the Tasmanian culture steppe (all specimens photographed in alcohol with the exemption of 13.36 which was photographed live): (25) cf. Dicyrtomina sp. 1 (dorsal view); (26) Sminthurinus mime (lateral view); (27) S. mime (dorsal view); (28) Sminthurinus tuberculatus (dorsal view); (29) Sminthurinus sp. 1 (dorsal view); (30) Sminthurinus elegans (typical colour form, dorsal view); (31) S. elegans dark form, dorsal view); (32) Prorastriopes quinquefasciatus (dorsal view); (33) Sphaeridia pumilis (lateral view); (34) Jeanenotia stachi australiensis; (♀ , lateral view); (35) J. stachi australiensis (♂ , dorsal view); (36) Sminthurus viridis with eggs (dorsal view); (37) S. viridis (mottled colour form, dorso-lateral view); (38) Deuterosminthurus sulphureus mediterraneus (lateral view); (39) Deuterosminthurus pallipes (dorso-lateral view). Scale line 0.25 mm Figs 30, 31; scale line 0.5 mm Figs 26, 27, 28, 29, 32, 33, 34, 35, 38, 39; scale line 1 mm Figs 25, 36, 37.


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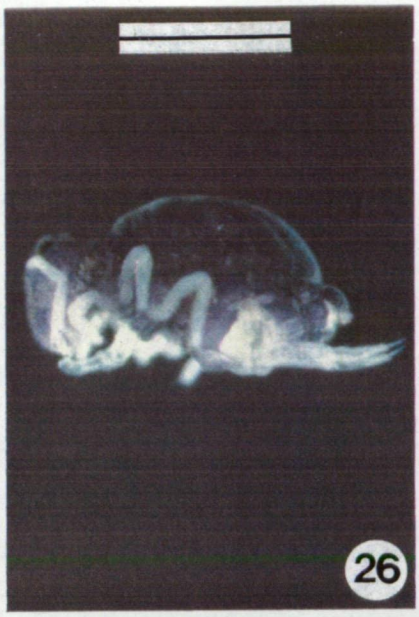
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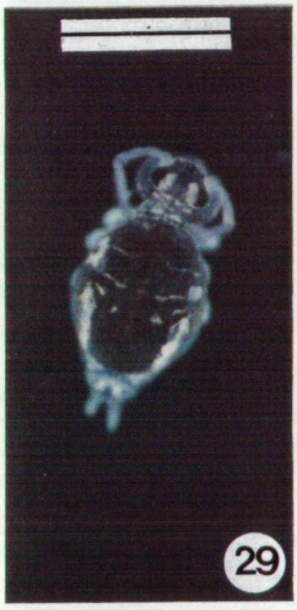
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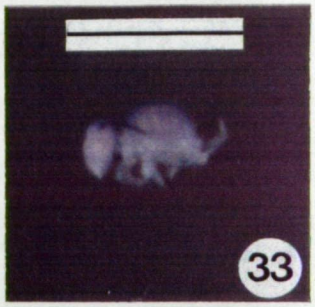
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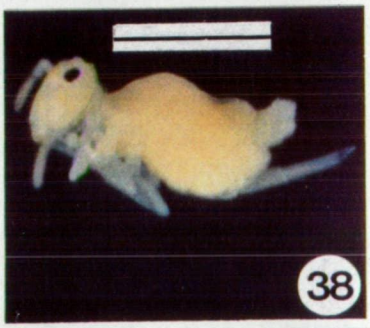
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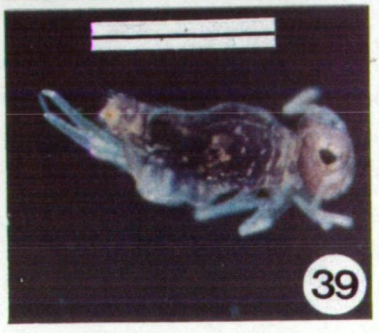
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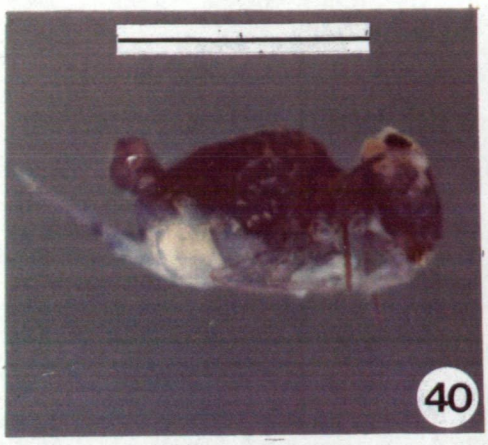
Figs. 13.40-13.50 Colour photographs of Collembola identified in the Tasmanian culture steppe (all specimens photographed in alcohol): (40) Bourletiella hortensis (lateral view); (41) B. hortensis (dorsal view); (42) B. viridescens (lateral view); (43) B. viridescens (dark colour form, dorsal view) (44) Katianna australis (lateral view); (45) K. australis (dorsal view); (46) K. mucina (dorsal view); (47) K. sp. cf. obscura (dorsal view); (48) K. ornata (dorso-lateral view); (49) K. oceanica var. schoetti (dorsal view); (50) K. sp. cf. pescotti (dorsal view). Scale line 0.5 mm Figs 43, 49, 50; scale line 1 mm Figs 40, 41, 42, 44, 45, 46, 47, 48.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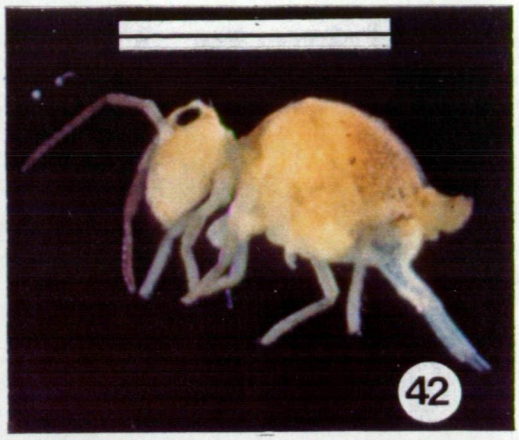
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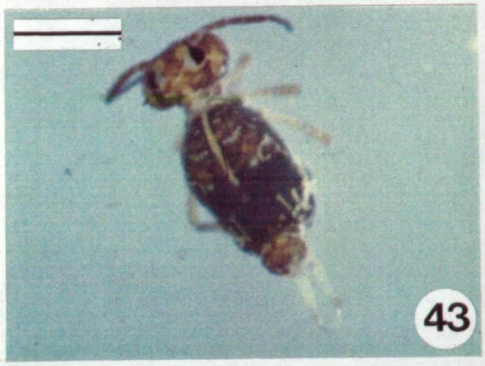
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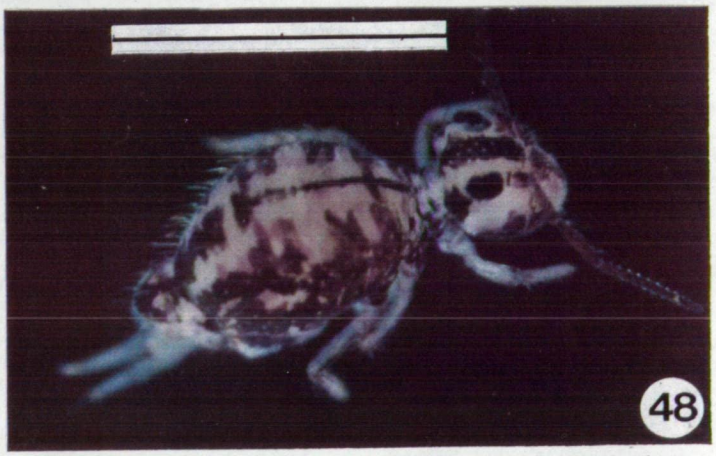
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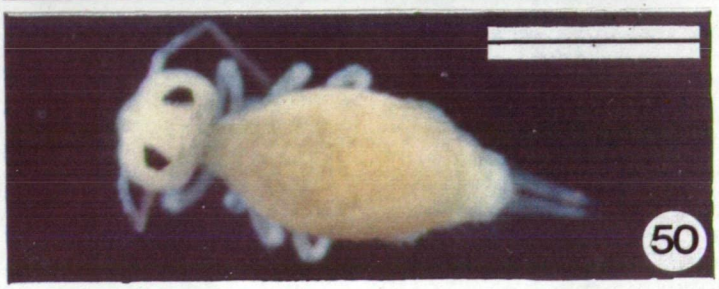
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Figs. 13.51-13.59 Colour photographs of Collembola identified in the Tasmanian culture steppe (all specimens photographed in alcohol): (51) Katianna sp. 1 (yellow-green colour form, dorsal view); (52) Katianna sp. 1 (striped colour form, dorsal view); (53) Entomobrya sp. cf. lanuginosa (dorsal view); (54) E. multifasciata (dorsal view); (55) E. unostrigata (dorsal view); (56) E. marginata (dorsal view); (57) E. atrocincta (dorsal view); (58) Isotomurus palustris (dorsal view); (59) Lepidocyrtus sp. 1 (lateral view). Scale line 0.5 mm Figs 53, 57; scale line 1 mm Figs 51, 52, 54, 55, 56, 58, 59.


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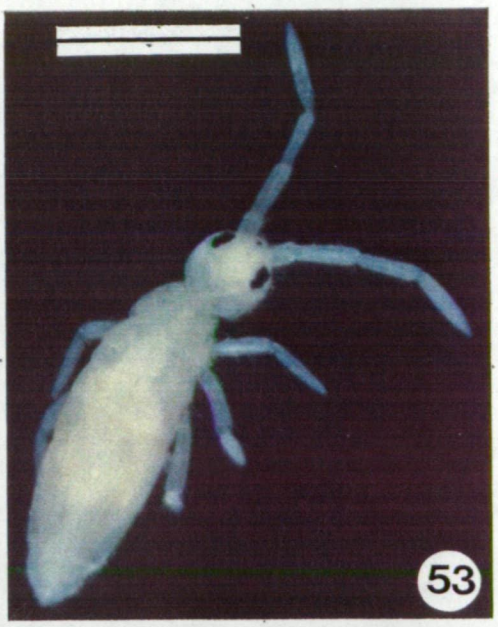
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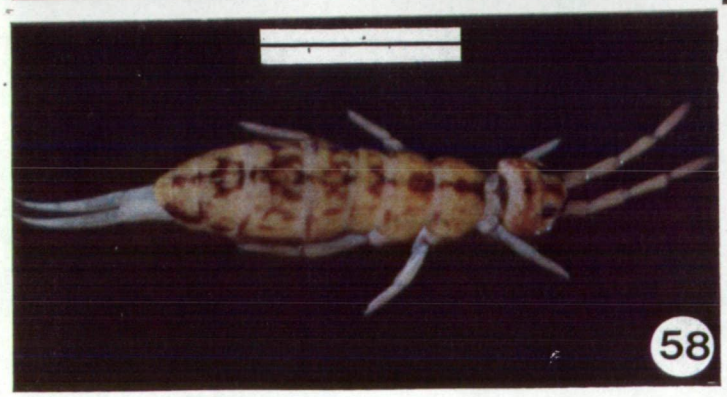
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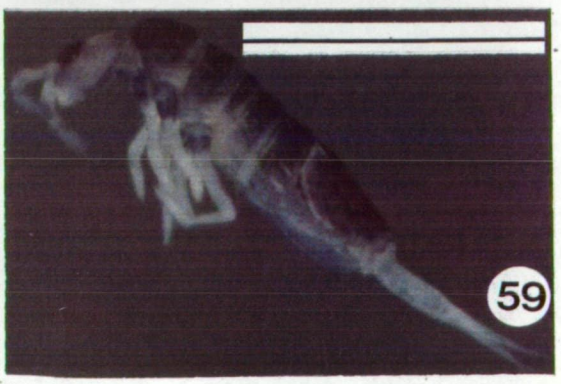
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Figs 13.60-13.69 Colour photographs of Collembola identified in the Tasmanian culture steppe (Figs 12.60-12.66 photographed in alcohol; Figs 12.67-12.69 photographed live): (60) Australotomurus echidnus (dorsal view); (61) Cryptopygus thermophilus (lateral view); (62) Isotoma tigrina (lateral view); (63) Neanura muscorum (dorso-lateral view); (64) Folsomia candida (lateral view); (65) Onychiurus sp. fimetarius gp. (lateral view); (66) Tullbergia sp. (lateral view); (67) Triacanthella sp. (live specimens aggregating on damaged strawberry fruit); (68) Hypogastrum vernalis (live specimens floating on the surface of water); (69) Brachystomella platensis (live specimens floating on the surface of water). Scale line 0.5 mm Figs 61, 64, 65, 69; scale line 1 mm Figs 60, 62, 63, 66, 67, 68.


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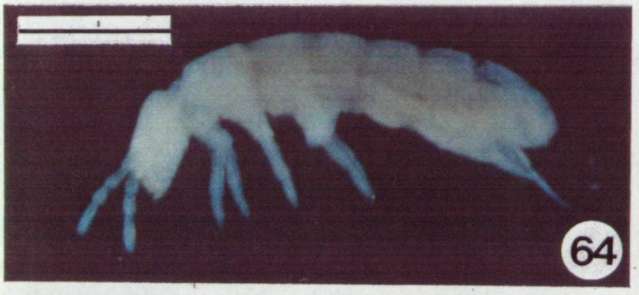
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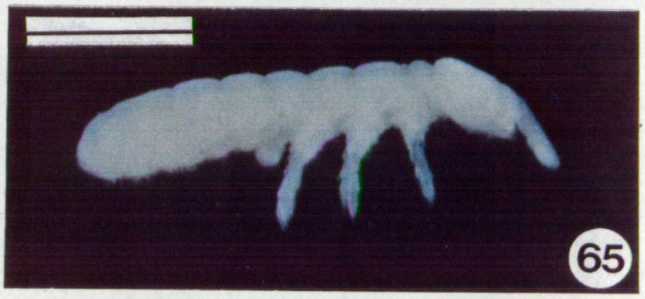
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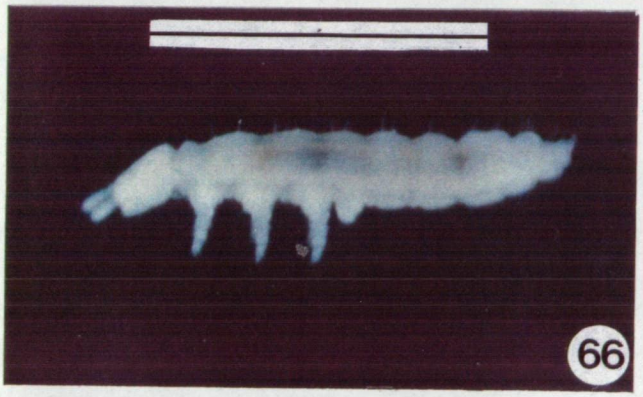
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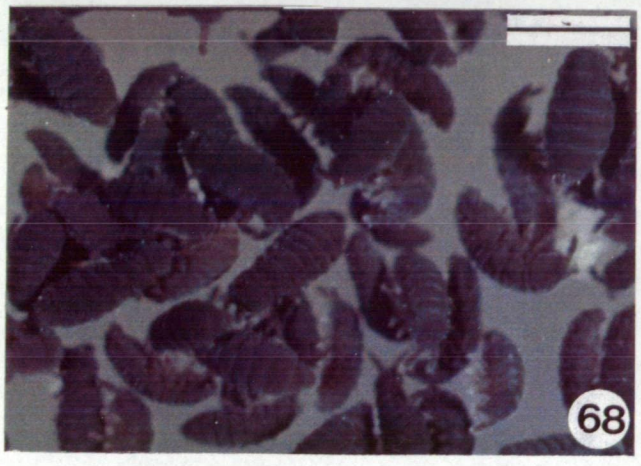
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KEY TO ONYCHIURIDAE OF THE TASMANIAN CULTURE STEPPE

Sub-families

Post-antennal organ (PAO) with numerous, simple tubercles (>60) (Fig. 13.70); 2, 3 or 4 exposed sensory clubs on antennae 3, smooth and slightly curved towards each other (Fig. 13.71); body slender and narrow (Fig. 13.66) .....sub-family Tullberginae

PAO not as above, with <<60 single lobes arranged eliptically (Fig. 13.72) or with 8-20 compound lobes (Fig. 13.73); sensory clubs of antennae 3 smooth or tuberculate not curved towards one another and behind 4-6 papillae (Fig. 13.74); body broader and flattened dorsoventally (Fig. 13.65) .....
.....sub-family Onychiurinae

Sub-family Tullberginae

1. Antennal base present, distinguished by cuticular granulations slightly smaller and more clustered than on rest of head (Fig. 13.75); two anal spines present dorsally on abdomen 6.....
.....Tullbergia spp. (Fig. 13.66)

   Area at base of antennae not distinguishable from rest of head; abdomen 6 with more than two anal spines .....Dinaphorura sp.

Sub-family Onychiurinae (genus Onychiurus)

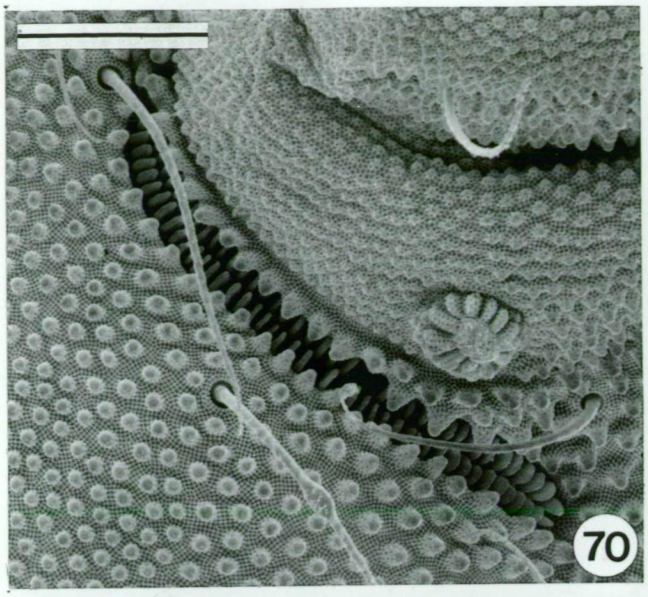
1. Anal spines present; lobes of PAO single not arranged in clusters (Fig. 13.72) (sub-genus Protophorura).....
.....Onychiurus (Protaphorura) armatus (Tullberg) group

   Anal spines present or absent; lobes of PAO arranged in clusters (Fig. 13.73) (Sub-genus Onychiurus).....2

2. Anal spines present.....Onychiurus (Onychiurus) ambulans (L.) group

   Anal spines absent..O. (Onychiurus) fimetarius (L.) group (Fig. 13.65)

Fig. 13.70-13.75 Electron micrographs of Onychiuridae: (70) PAO of Tullbergia sp; (71) sensory organ on antenna 3 of Tullbergia sp; (72) single lobes of post-antennal organ of Onychiurus sp. armatus gp.; (73) compound lobes of PAO of Onychiurus sp. fimetarius gp.; (74) papillae of sense organ on antenna 3 of Onychiurus sp. armatus gp.; (75) antennal base of Tullbergia sp. Scale line 10 µm Figs 71, 73; scale line 20 µm Figs 70, 72, 74, 75.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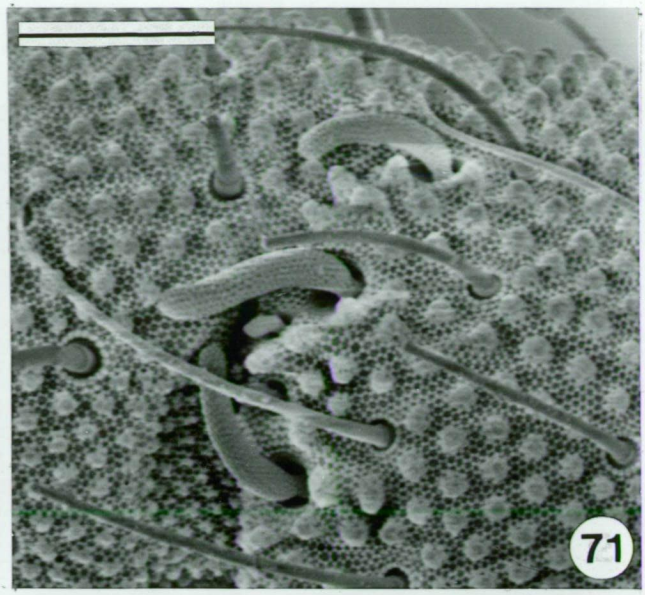
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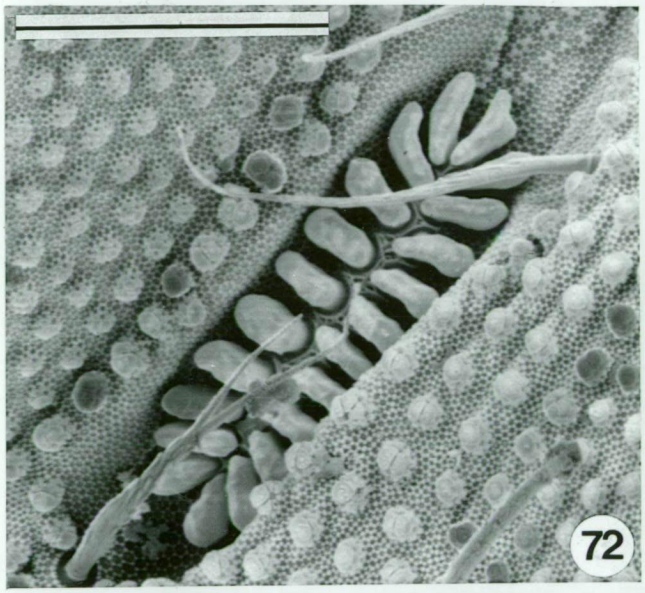
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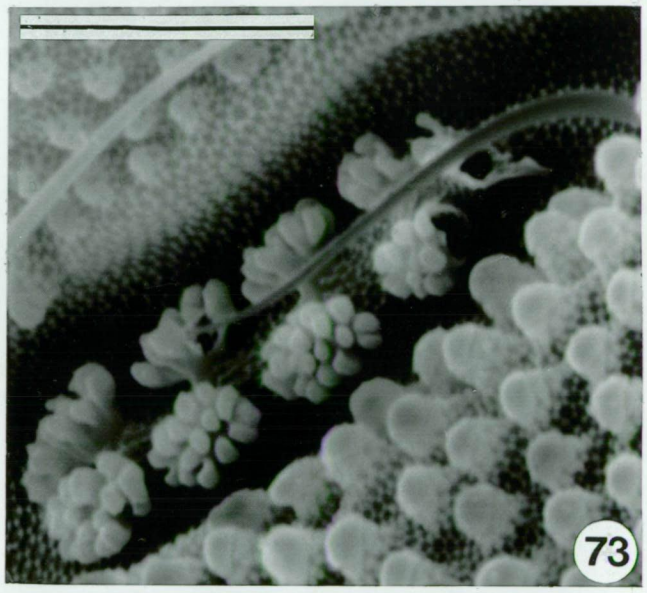
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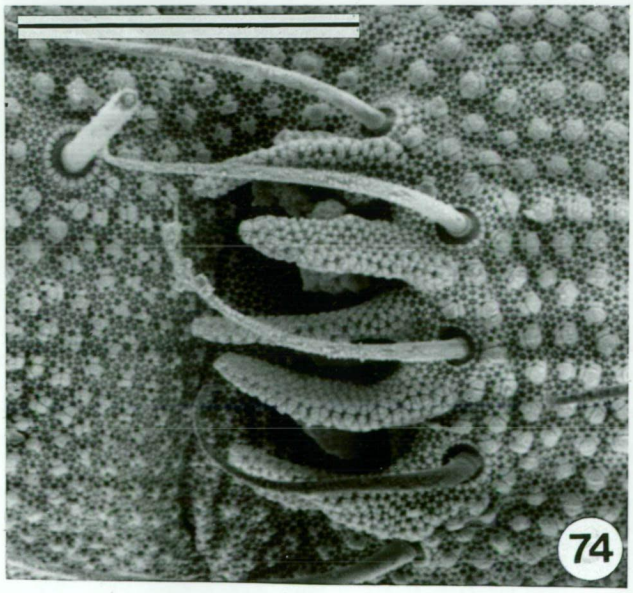
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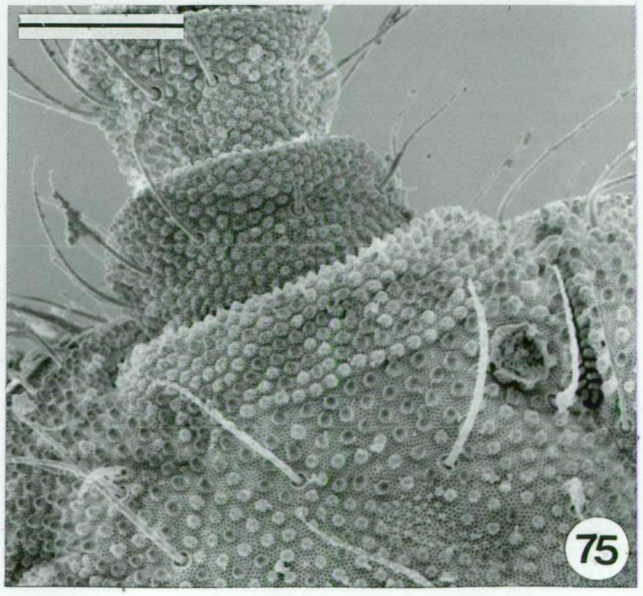
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KEY TO HYPOGASTRURA SPP. OF THE TASMANIAN CULTURE STEPPE

1. Eversible sac present between antennal segments 3 and 4 (Fig. 13.76); clavate tibiotarsal hairs absent; mucro (Fig. 13.77) rounded apically with large traingular lobe.....2 (sub-genus Ceratophysella)

   Eversible sac absent between antennal segments 3 and 4; clavate tibiotarsal hairs present, mucro tapering, pointed .....
   .....4 (sub-genus Hypogastrura)

2. Cuticle of abdomen 5 with an area of large granules swollen mid-dorsally between median macrochaetae and projecting posteriorly over smaller granules ajacent to abdomen 6 (Fig. 13.78); abdomen 4 with 2 + 2 microchaetae between median macrochaetae (Fig. 13.79).....
   .....Hypogastrura (Ceratophysella) gibbosa (Bagnall)

   Abdomen 5 without swollen area of granules mid-dorsally but cuticular granules often larger in mid-dorsal region; abdomen 4 with 3 + 3 microchaetae between median macrochaetae (Fig. 13.80).....3

3. Abdomen 5 with 4 microchaetae between median macrochaetae (Fig. 13.81)
   .....Hypogastrura (C.) denticulata (Bagnall)

   Abdomen 5 with 2 microchaetae between median macrochaetae (Fig. 13.82)
   .....Hypogastrura (C.) sp. cf. engadinensis Gisin*

4. Legs 1, 2 and 3 with 3 clavate tibiotarsal setae equidistant from base of claw (Fig. 13.88); mucro with broad lamella (Fig. 13.83)
   .....Hypogastrura (Hypogastrura) viatica (Tullberg)

   Leg 1 with 2 clavate tibiotarsal setae and legs 2 and 3 with 3 clavate tibiotarsal setae not equidistant from base of claw, median seta being more apical than the other(s) (Figs 13.89, 13.90); mucro (Fig. 13.84) with narrow, less prominant lamella.....
   .....Hypogastrura (H.) purpurescens (Lubbock)

   Legs 1, 2 and 3 with one clavate tibiotarsal hair (Fig. 13.91) 5

5. First antennal segment with 8 setae which includes a supplementary 'p' seta slightly posterior to other setae (Fig. 13.85).....
   ..... Hypogastrura (H.) assimilis (Krausbauer)

   First antennal segment with 7 setae, supplementary 'p' seta absent ..6

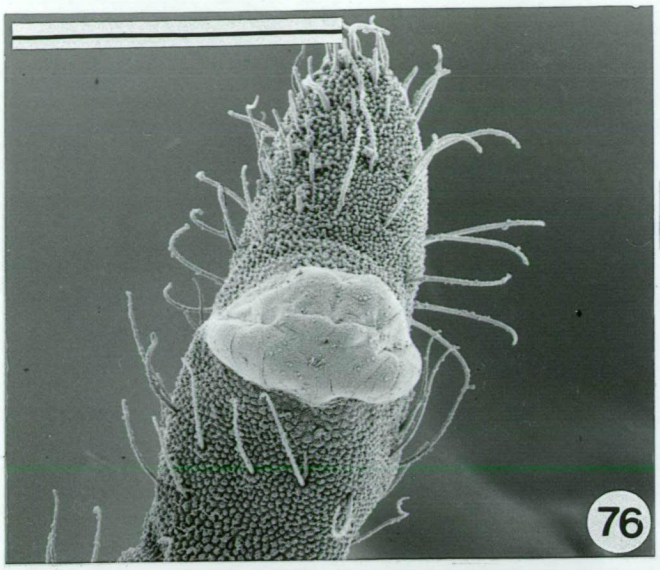
6. Mucro (Fig. 13.86) approximately one-half the length of the dens, gradually tapering towards apex with straight anterior margin; tip of mucro tooth-like and bent upwards .....
   .....Hypogastrura (H.) manubrialis (Tullberg)

Mucro (Fig. 13.87) approximately one-third the length of the dens with weakly bent anterior margin; tip of mucro narrow and straight; mucronal lamella notched near apex .....
.....*Hypogastrura* (*H.*) *vernalis* (Carl)

* The identification cannot be confirmed until examination of type material and it is possible that more than one species is involved here, neither of which are *engadinensis*. Gisin (1960) separated *engadinensis* from *denticulata* on the basis of fifth abdominal segment chaetotaxy. However, Christinsen and Bellinger (1980a) state that some European populations have been seen in which both types were present and many intergradations exist. They have grouped these related forms under the name *denticulata*, pending a more detailed study of the complex.

Figs 13.76-13.81 Electron micrographs of Hypogastrura* spp. : (76) eversible sac between antennal segments 3 and 4 of H. (C.) denticulata; (77) mucro of H. denticulata; (78) abdomen 5 of H. gibbosa showing area of large granules between median microchaetae; (79) abdomen 4 of H. gibbosa showing 2 + 2 microchaetae between median macrochaetae; (80) abdomen 4 of H. denticulata showing 3 + 3 microchaetae between median macrochaetae; (81) abdomen 5 of H. denticulata showing 4 microchaetae between median macrochaetae. Scale line 20 μm Fig. 77; scale line 30 μm Fig. 78; scale line 50 μm Figs 79, 80, 81; scale line 100 μm Fig. 76.

*Fig. 13.78 is a 35 mm black and white photomicrograph taken with an Olympus^{R} Vanox microscope fitted with Nomarski differential interference contrast equipment.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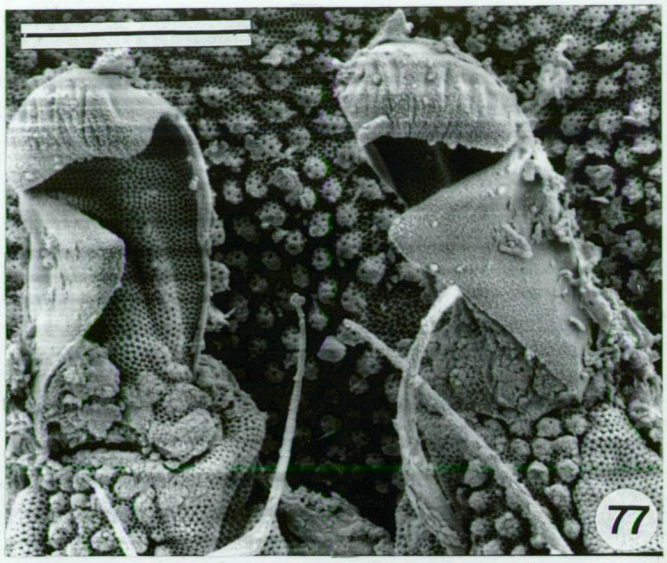
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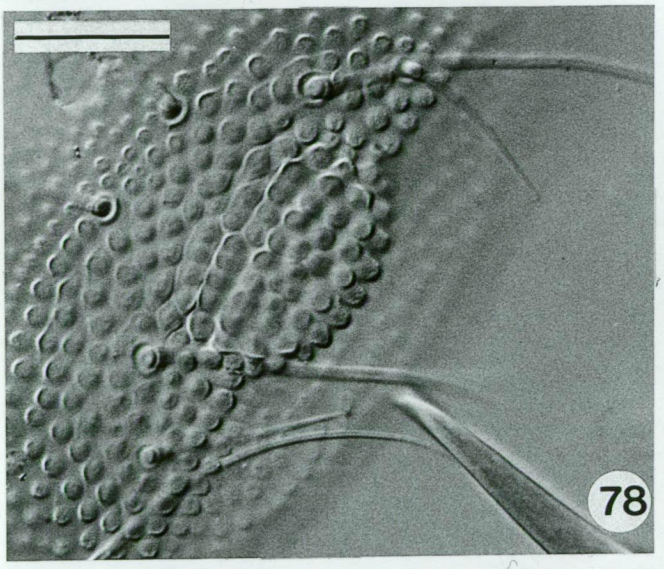
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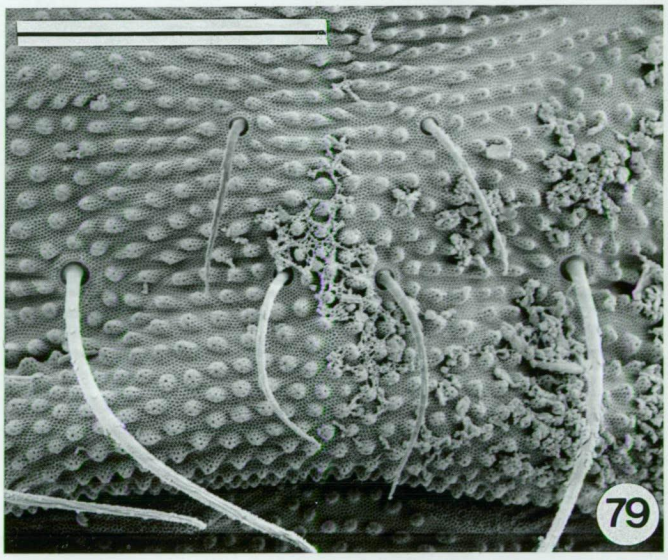
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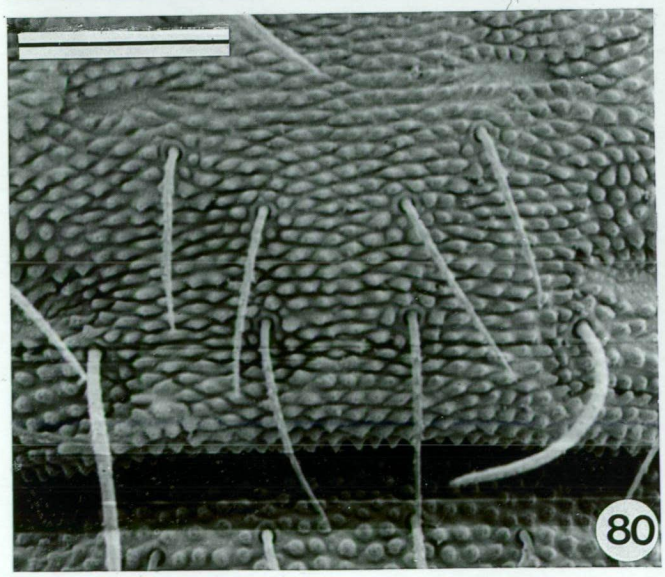
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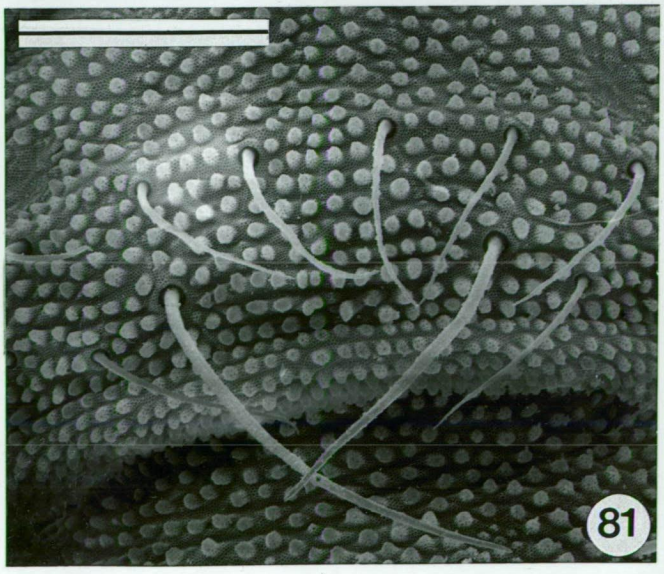
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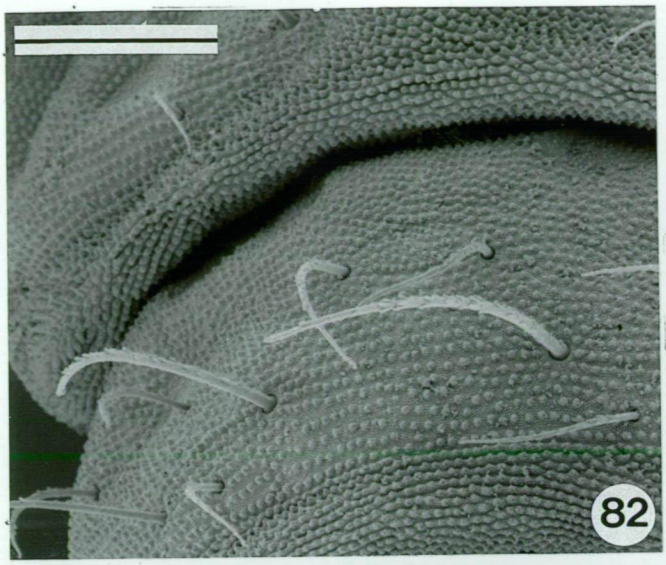
Figs 13.82-13.87 Electron micrographs of Hypogastrura spp.: (82) abdomen 5 of H. sp. cf. engadinensis showing 2 microchaetae between median macrochaetae; (83) mucro of H. viatica; (84) mucrones of H. purpurescens (lateral and posterior views); (85) first antennal segment of H. assimilis showing supplementary 'p' seta (arrowed); (86) mucrones and dentes of H. manubrialis (anterior view); (87) mucrones of H. vernalis (posterior and lateral views, with lateral view showing notch in mucronal lamella near apex) and posterio-lateral view of dens. Scale line 10 µm Fig. 83; scale line 20 µm Figs 84, 85, 86, 87; scale line 50 µm Fig. 82.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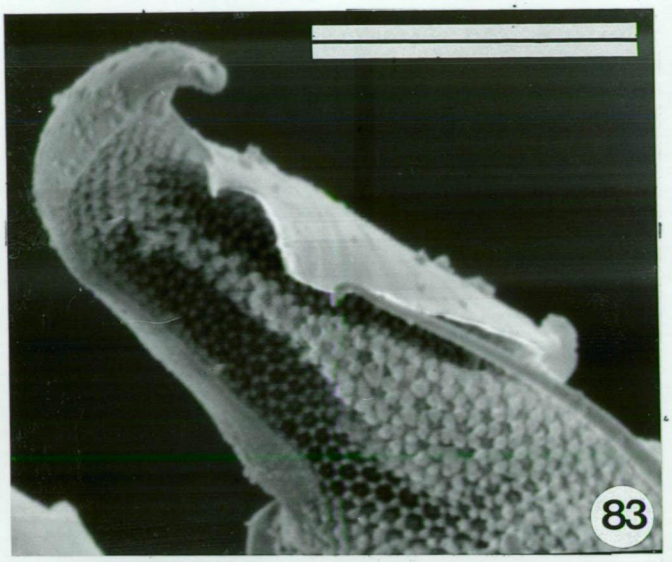
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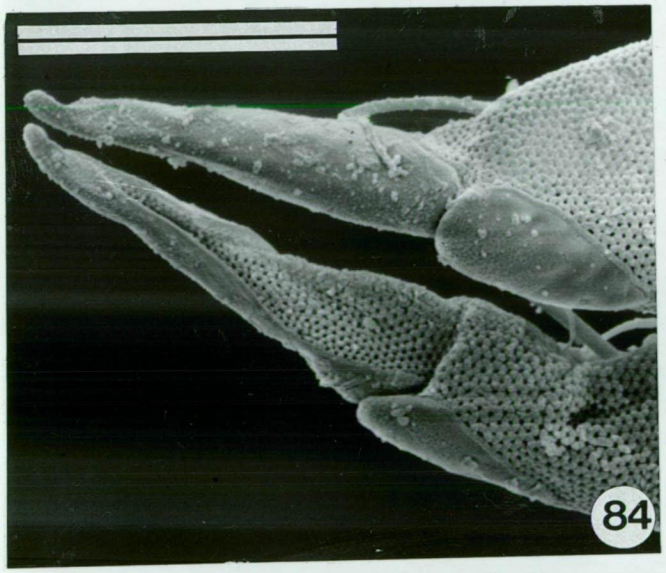
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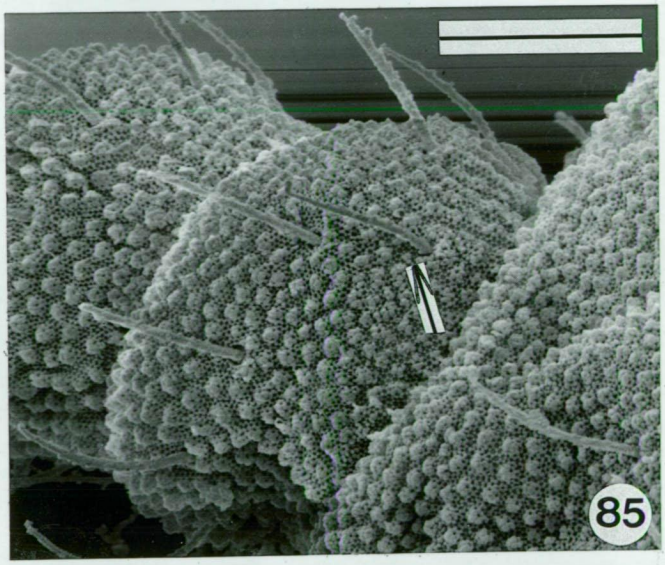
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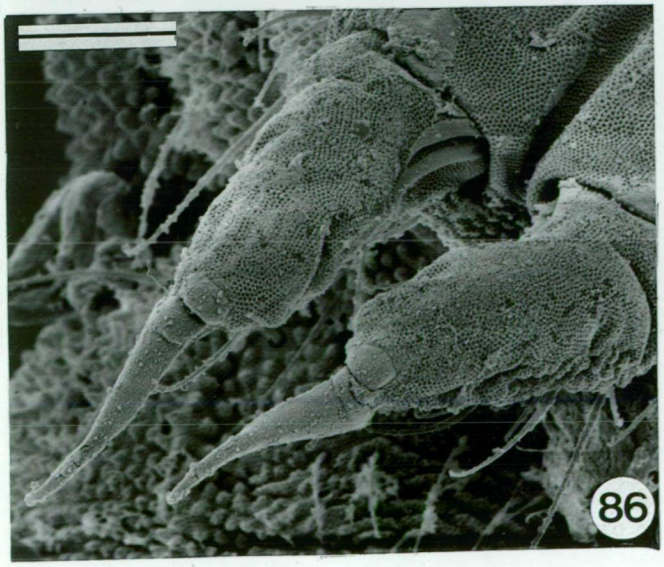
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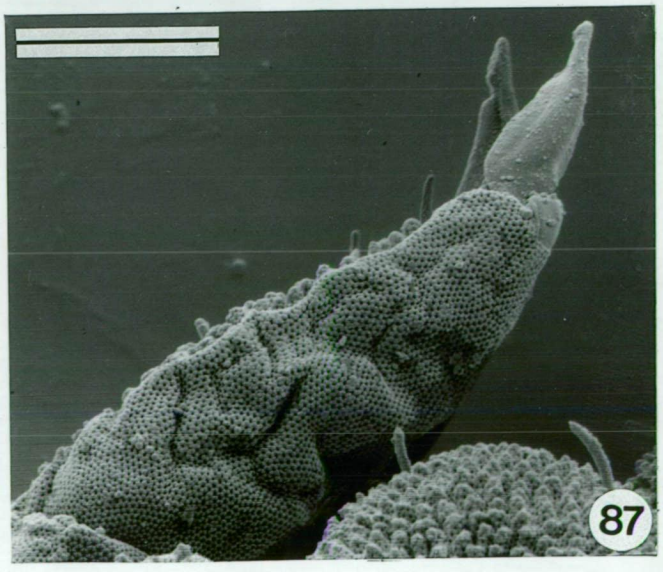
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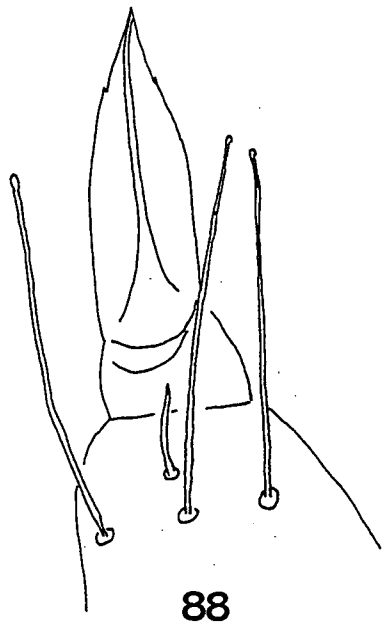
Figs 13.88-13.91 Line drawings of claws and tibiotarsi of Hypogastrura spp. (x400) : (88) leg 2 of H. viatica showing 3 clavate tibiotarsal setae equidistant from base of claw; (89) leg 1 of H. purpurescens showing 2 clavate tibiotarsal setae not equidistant from base of claw; (90) leg 2 of H. purpurescens showing 3 clavate tibiotarsal setae not equidistant from base of claw; (91) leg 1 of H.manubrialis showing 1 clavate tibiotarsal hair.



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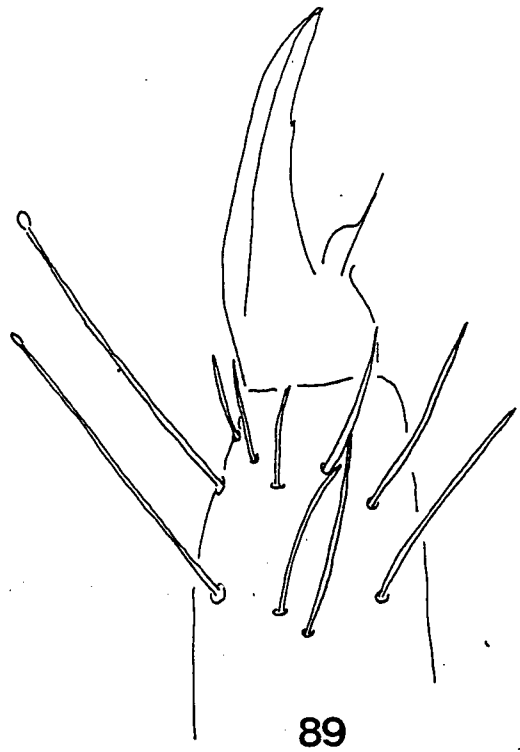

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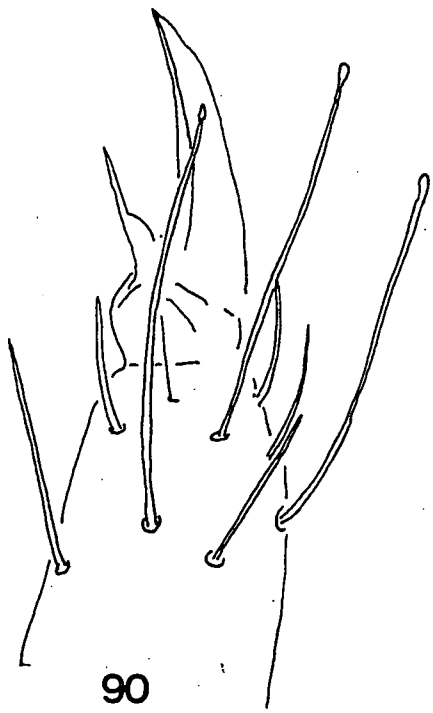

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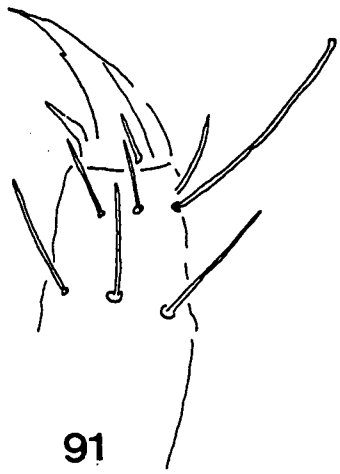

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APPENDIX

PUBLICATIONS ARISING FROM STUDIES DESCRIBED IN THIS THESIS

IRESON, J.E. (1982) - A re-examination of the distribution of the pasture snout mite, Bdellodes lapidaria (Kramer) (Acari: Bdellidae) and the lucerne flea, Sminthurus viridis (L.) (Collembola: Sminthuridae) in Tasmania. J. Aust. ent. Soc. 21: 251-255.

IRESON, J.E. and MILLER, L.A. (1983) - Susceptibility of the collembolan Sminthurus viridis to the insect parasitic nematodes Neoaplectana bibionis and Heterorhabditis heliothidis. Ent. exp.appl. 34: 342-343.

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GREENSLADE, P. and IRESON, J.E. (1986) - Collembola of the southern Australian culture steppe and urban environments: A review of their pest status and key to identification. J. Aust. ent. Soc. 25: 273-291.

ANSWERS TO POINTS RAISED BY EXAMINERS - Ph.D. Thesis

(JOHN IRESON)

Comments by Dr. Robert A. Byers.

Dr. Byers raises 14 points 13 of which relate to typographical errors or are questions on English expression. All of these queries have been attended to.

With regard to the question regarding the steep fall of *Onychiurus* populations in control plots (p. 281), Dr. Byers questions the possibility of Collembola in untreated plots moving into the treated plots and being killed.

I consider this to be unlikely as each of the plots were situated 3.5 metres apart. Furthermore, significant movement by *Onychiurus* tends to occur vertically, rather than horizontally (see para 1, p. 282). Once in the root zone, populations tend to aggregate rather than disperse at random. The secretion of aggregation pheremones may be involved in this behaviour (see para. 2 p. 282).

Comments by Dr. M. M. H. Wallace

Dr. Wallace raises 4 points 3 of which are typographical and have been attended to. The fourth point relates to the modification of the following sentence (p. 120, Para. 5, line 2):

"The fact that severe infestations of *S. viridis* continue to occur in Tasmanian pastures indicates that the naturally occurring predators are unable to prevent the rapid build-up in large numbers that occurs annually during autumn and spring".

Dr. Wallace requested that this be modified and I have done so as follows:

"The fact that severe infestations of *S. viridis* continue to occur in Tasmanian pastures indicates that the naturally occurring predators in the established complex are unable to effectively reduce the number and frequency of severe infestations that occur annually during autumn and spring".

Comments by Dr. Clive Wall

Dr. Wall makes specific comments on each Chapter and, where necessary, these have been addressed as follows:

Chapter 1

Some typographical errors in this chapter are indicated and have been addressed.

Chapter 3

1. Comments on the presence/absence criterion

As far as this work is concerned, the use of this criterion has worked well. Obviously, because of predation, short cropping of grass and other factors such as seasonality, one would not always expect to collect species such as *B. lapidaria* in a sample. However, for this work Tasmania was divided into climatic areas which were sampled in detail over several years and in all seasons. The surveys prime achievement was to show that *B. lapidaria* was poorly established (almost absent) from pastures in the far north-west corner of the State although present and widespread elsewhere.

I should add that other work with which I have been engaged has involved fortnightly core and suction sampling over at least 12 months in sample plots located in the far north-west (at Irishtown). This sampling has confirmed the results of this survey.

2. 'No discussion about previous survey work'

This comment is incorrect. Only one previous survey was carried out (by Wallace and Mahon (1971)) (see reference list) and this work and their Tasmanian results is detailed in the introduction to this chapter on p. 65. Further (more detailed) discussion of the Wallace and Mahon survey is made in the discussion section on p. 73.

3. Citation of unpublished data on P. 81.

I can produce these data if required. However, if the referee is suggesting that the cited (unpublished) data should actually be added to the text of the thesis in Chapter 3, then I feel it is an unnecessary requirement, as the work cited is outside the scope of the objectives of this Chapter and would add little to the discussion. In fact, the discussions would not be affected if the line referring to the unpublished data was erased.

The work referred to is a preliminary trial carried out during 1986, to evaluate the effect of *S. viridis* on pastures and the correct timing of insecticide treatments for optimum control. To explain the methodology and adequately present even a summary of the data would require a major re-organisation of chapter 3, which simply isn't worth it just to substantiate a statement, which, as I have said really adds nothing to the discussion of chapter 3. A detailed (unpublished) report of the trial work can, however, is available for perusal.

4. Exhibition of all sample sites in Figs 3.1 - 3.4.

I don't see how the exhibition of all sample sites would achieve anything other than clutter the maps (Figs 3.1 - 3.4), given the fact that 280 samples were taken in total. The aim of these maps (as presented) is to show the distribution of *B. lapidaria/S. viridis* (i.e. their *presence*) in relation to the climatic zones of Walter and Leith and the 800 and 1200mm isohyets.

In contrast the *absence* of *B. lapidaria* in the far north-west was an important result and all sample sites for this species are shown in Fig 3.5.

Chapter 4

1. 'Argument about predator efficiency untenable'

If Dr. Wall finds this argument untenable then he appears to have misunderstood my argument. What I have said is that because a proportion of the *S. viridis* population is *nearly* always outside the range of *B. lapidaria*, predation *efficiency is reduced*. This does not mean that all predation pressure on a mixed age *S. viridis* population is removed, nor was it meant to imply it. Obviously some form of pressure would exist unless all *S. viridis* in the population were beyond prey range.

2. 'Collapse of population of *B. lapidaria* well before collapse of *S. viridis* population (Fig 4.1) not addressed in discussion'

I have discussed, at length, the ineffectiveness of *B. lapidaria* in relation to climate in chaps 3 and 4, which I feel is the main reason for its poor performance. I consider that the point raised by Dr. Wall, in relation to the frequent collapse of *B. lapidaria* populations well before those of *S. viridis*, is covered in the discussion on p. 93, para. 2.

Chapter 5

1. Dr. Wall asks if *P. quisquiliarum* could be a recent introduction.

This is possible, but its low frequency could equally be explainable by competition for an available niche with *P. longicornis* (or other predators), or the effect of other environmental factors (e.g. climate) may be more restricting on this species than on *P. longicornis*.

2. Dr. Wall suggests that the lack of establishment of *A. salicinus* in southern Tasmania is not all that significant when only 1,200 and 500 were released, and that no attempt was made to discuss this. He also considers that this clashes with a conclusion in the next chapter (6), that serious introduction attempts should involve much larger numbers of individuals.

I consider that releases of 1,200 and 500 specimens of *Anystis salicinus* would be enough to get this species established in Tasmania. The West Australian Dept. of Agriculture has been successful in getting this species established in pastures in Western Australia using similar numbers.

My comment (in ch. 6) that serious introduction attempts should involve much larger numbers of individuals was referring to *Neomolgus capillatus* not *A. salicinus*. Furthermore, I was lamenting the fact that a shipment of *Neomolgus* from Montpellier consisted of only 150 specimens which is a low number for a European shipment given the fact that you can expect at least 20% mortality (see Table 6.2). In contrast, all *Anystis* shipments from W.A. have arrived almost 100% intact.

Chapters 6 and 7

Dr. Wall states that he was not impressed with the way the biological control work was carried out.

I am extremely disappointed with Dr. Walls comments on these Chapters.

In particular, the statement that the work should have been planned more carefully is easily refutable when all details of the project background are fully known. Although I went to great lengths (in the text) to point out the difficulties involved in the mite introduction programme which were beyond my control, he seems to have completely overlooked what was said.

I stated in the text (p. 125 and p. 129 - 130) that I considered the initial numbers of *N. capillatus* received in Tasmania from the W.A. Dept. of Agriculture and from CSIRO to be too low to expect field establishment. For this reason (and I clearly state it on p. 125) the shipment from W.A. was used for lab. experiments (the aims of which were also clearly outlined in the text).

I had no control over the number of mites that were forwarded (on any occasion). These early collections, in particular, were gratis, as no funds were available. Several efforts were made over a period of years to get CSIRO to collect and ship large numbers of mites, (comparable to the shipments that Wallace had made previously (to W.A.). When all attempts failed (and this is documented on Tasmanian Department of Primary Industry Files) it took a further two years to get private funding for CIBC to do the job (which also involved a personal visit by me to Delemont). This is all stated in the text of the thesis, as well as the quarantine problems we had to overcome.

As far as being slow off the mark with investigations on parasitic nematodes, it is worth remembering that *S. viridis* is an epigaeic and not a euedaphic collembolan. *Onychiurus* are less mobile than *S. viridis* because they lack a furcula. For this reason, it is possible that nematodes may not work in a field situation with *S. viridis*, although I hope I can follow-up my laboratory work. The laboratory work is the first recorded infestation of an epigaeic collembolan with parasitic nematodes. However, to say that this work be given preference over establishing mite predators in Tasmania (a method known to be effective, even though they are slow to spread) is unfounded. Funds have been a limiting factor for the work, and funding bodies are often slow to fund some projects as Dr. Wall should appreciate (i.e. I have attempted to get funds for the nematode investigations but have been unsuccessful, however, as previously stated I was able to get funds for the importation of mite predators).

The bio-control programme with *Neomolgus*, will, by its very nature be long term. However, the additional results from the monitoring of *Neomolgus* at established Tasmanian sites in the 8 months since my thesis was submitted offer further encouragement. I have also since discovered that the fungus *Metarhizium anisopliae* is parasitic on *S. viridis* in cultures. Funds are now being sought to investigate this result under field conditions and the work will (hopefully) commence in January, 1992.

Chapter 9

Dr. Wall states that 'Laboratory tests which do not involve choice should be viewed with great caution. The fact that *Katianna* fed on soft plant tissue in this type of situation is hardly significant, in view of the previous discussion about *Bourletiella*'.

Again, the referee seems to have misinterpreted what I have said.

I am well aware that laboratory tests which do not involve freedom of choice should be viewed with caution. I state on p. 245 (3rd Para.) that the use of the culture studies was to determine whether or not a species can feed on a particular plant and that care must be taken in extrapolating results to a field situation while there are alternative foods. The culture studies are a useful follow-up if a species is suspected (or associated) with causing primary damage to a particular plant. The culture studies can then confirm whether the collembolan can actually feed on the particular plant.

The fact that *Katianna* spp. did feed on soft green tissues (of some plant species) suggested they had the *potential to cause primary damage, just as Bourletiella* spp. sometimes do. I then stated that this, however, was unlikely because of the preference of *Katianna* for a closed habitat rather than an open field crop habitat. Furthermore, as with *Bourletiella* I would expect that preferred food sources would be microbial, and that green plant material might only be a possible food if preferred food sources were limited (probably an unlikely scenario).

Chapter 10

Dr. Wall comments that he found himself asking the question at the end of the Chapter "does *Onychiurus* cause economic damage, even though it may be a secondary agent?"

I do state in the Discussion (p. 176) that I consider *Onychiurus* should be classed as a facultative rather than an obligate root feeder. Further more, the thrust of the discussion that follows this statement indicates that under certain conditions, *Onychiurus* can cause root damage.

However, when *Onychiurus* is associated with damage to crops, other factors which may predispose the particular crop to attack should also be considered.

Chapter 11

Dr. Wall states that the use of granular chlorpyrifos is not discussed.

The following passage has therefore been added to the discussion on p. 282, para. 2: "For example, the efficacy of the granular form of chlorpyrifos ('Suscon') could be investigated. The chemical is registered in some Australian states (e.g. Queensland, for control of cane grub) but not in Tasmania. Use of the granular form would overcome the problem of the lack of persistence with the emulsifiable concentrate formulation, as a range of granular formulations are available which enable the active ingredient to be released over periods ranging from 150 days to 3 years. Furthermore, the granules can be drilled directly into the furrows with

the seed. However, it is, of course, also possible that chlorpyrifos is ineffective against *Onychiurus* no matter what form it is in".

Ireson, J. E. (1982) A re-examination of the distribution of the pasture snout mite, Bdellodes lapidaria (Kramer) (Acari: Bdellidae) and the lucerne flea, Sminthurus viridis (L.) (Collembola: Sminthuridae) in Tasmania. J. Aust. ent. Soc. 21: 251-255

BOOK REVIEW

Proceedings of the 3rd International Symposium on Trichoptera: G. Moretti (ed.) 1981. Junk: The Hague, xx + 449 pp. US$89.

This book represents the papers given at the 3rd International Symposium of Trichoptera held at Perugia from July 28 to August 2, 1980. The table of contents is overwhelming with a listing of 54 papers which editor Moretti advises, in the preface, deal with "the morphology, ultrastructure, systematics, taxonomy, phylogenesis, palaeontology, zoogeography, ecology, population dynamics, distribution, pollution, classification, biological cycles, sex ratios, histology, cytology, biochemistry, physiology and parasitology of both larvae and adult Trichoptera".

Indeed, they are all here, arranged in alphabetical order of the first or sole author. Read in their entirety from A to Z these papers give one an insight into the level and diversity of Trichopteran studies, but were they really delivered in this order? A grouping of papers under appropriate sections would have been simple to arrange and would have facilitated reading of, and access to, the papers.

For example a section on systematics could have been prefaced by Higler's "Caddis fly systematics up to 1960 and a review of the genera (Insecta: Trichoptera)" and followed by Morse's rigorous analysis of the phylogeny and classification of the Leptoceridae, Nielsen's detailed study "On the evolution of the phallus and other male terminalia in the Hydropsychidae", Wiggins' "Considerations on the relevance of immature stages to the systematics of Trichoptera" and others. Possibly Botosaneanu's "Ordo Trichoptera et *Homo insapiens*", a summary (in French) of published and unpublished information on man's effects on Trichopteran distribution and abundance would have been a fitting introduction to the series of interesting papers documenting changes resulting from environmental disruption (e.g. Prat, "The influence of reservoir discharge on benthic fauna in the River Ter, N.E. Spain", Resh *et al.*, "Responses of the Sericostomatid caddisfly *Gumaga nigricula* (McL.) to environmental disruption", Stanford and Ward "Preliminiary interpretations of the distribution of Hydropsychidae in a regulated river"; with papers grouped in this way, the book may have attracted a wider interest.

Papers on morphology, ecology and other topics could have comprised further strong sections. The distributional studies and check lists are a mixture of broader regional and narrower parochial studies; I wonder if the latter are somewhat out of place in a symposium.

On the editorial side a number of contributions, including those by Moretti and his co-workers, Nielsen, and Wilkinson, gave references not cited in the test and/or omit others; some of the figures and tables presented are so complex and badly printed as to be incomprehensible (e.g. many in the paper by Kiss, "Trichoptera in the Ilona stream of the Matra Mountains, North Hungary"). A "paper" by Botosaneanu and Wichard entitled "Trichoptera from the Baltic Amber" consists only of a four line "summary"; no editorial explanation is given for this brevity. Referrals by Siegenthaler in "Trichoptera of Western Switzerland" to maps 1–7 are also somewhat disconcerting in the absence of any maps. Referencing throughout the volume was abbreviated to save space and thus cut costs; fuller referencing would have been to advantage.

Waiving these criticisms aside, I can see enormous value in being able to readily assess, compare, and contrast so many diverse studies in Trichopteran biology, including works by many of the major contributors of today.

Two papers are of particular interest to Australian readers. Neboiss' "Distribution of Trichoptera families in Australia with comments on the composition of fauna in the south-west" is the first overview of the distribution and relationships of Australian caddis-flies since the work of Mosely and Kimmins in 1953, and Morse's "A phylogeny and classification of family-group taxa of Leptoceridae (Trichoptera)" will be invaluable to persons working on that family, which is so widespread and abundant in Australia.

If Trichoptera are your primary concern then perhaps US$89 is not too high a price to pay for the potential generation of new ideas. It does seem a high price, though, for such a volume, and I would suggest that the better tactic would be to ensure access to a library copy.

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Ireson, J.E. and Miller, L.A. (1983) - Susceptibility of the collembolan Sminthurus viridis to the insect parasitic nematodes Neoaplectana bibionis and Heterorhabditis heliothidis. Ent. exp.appl. 34: 342-343

Ireson, J.E., 1984, The effectiveness of Bdellodes lapidaria (Kramer) (Acari: Bdellidae) as a predator of Sminthurus viridis (L.) (Collembola: Sminthuridae) in north-west Tasmania. J. Aust. ent. Soc. 23: 185-191

RAPID PUBLICATION NOTE

METOPOLOPHIUM DIRHODUM (WALKER) (HOMOPTERA: APHIDIDAE) NEWLY RECORDED FROM AUSTRALIA

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Abstract

Metopolophium dirhodum (Walker), the rose-grain aphid, is recorded for the first time from Australia.

Nineteen species of Aphididae are recorded from graminaceous hosts in Australia but only 4 of these commonly colonize cereals: *Rhopalosiphum maidis* (Fitch), *R. padi* (L.), *Sitobion miscanthi* (Takahashi) and a subterranean species, *R. rufiabdominalis* (Sasaki). A serious pest of cereals overseas, *Metopolophium dirhodum* (Walker), has recently been found infesting barley in New South Wales, and is hereby recorded for the first time from Australia.

Metopolophium dirhodum (Walker)

ex Hordeum vulgare L., NEW SOUTH WALES: Bemboka, 16.vi.1984, apterae [apt.] & alatae viviparae [al.] (K. Helms, P. M. Waterhouse, H. Kemp); *ex cult. Avena sativa* L., AUSTRALIAN CAPITAL TERRITORY: Black Mtn (glasshouse, 15°C, 16h photophase), 13.vii.1984, apt., al., ♂♂ (K.H., P.M.W.).

M. dirhodum, the rose-grain aphid, is palaearctic in origin; its present range covers Europe, the Middle East, India, China, North and South Africa, North and South America, and also New Zealand, where it was first detected in December 1981 and is now widespread. *M. dirhodum* is a host-alternating (heteroecious) species, which infests the leaves and buds of *Rosa* and occasionally *Agrimonia* and *Fragaria* (all Rosaceae), as primary hosts, and the leaves of grasses and cereals (Poaceae) and occasionally *Iris* (Iridaceae), as secondary hosts. Barley is a preferred host. Though predominantly holocyclic in Europe, overwintering in the egg stage on rose, it may also overwinter anholocyclically as parthenogenetic viviparae on grasses and cereals. In New Zealand, so far it has been recorded only from graminaceous hosts. *M. dirhodum* is a vector of the luteoviruses, barley yellow dwarf and beet western yellows. It is reported to be the second most abundant cereal aphid in Britain and the most serious cereal aphid pest in South America. However, except for the North American pest, *Schizaphis graminum* (Rondani), cereal aphids have only recently reached pest status; for instance, in Britain, outbreaks of varying severity have occurred only since 1968. These have been attributed to recent changes in cultural practices (Vickerman and Wratten 1979; Carter *et al.* 1980; Sunde in press).

Eastop (1966) and Prior (1975) have provided keys for the identification of cereal aphids, and Stroyan (1982), for species of *Metopolophium*.

The pest status of *M. dirhodum* in Australia is difficult to predict and could depend on various climatic, biotic and cultural factors, including the acceptability of Australian grass species and cereal cultivars, and the extent to which holocycly is induced. The degree of holocycly could affect the incidence of anholocycly on winter cereals and the importance of the abundant primary host, rose, as an annual source of infestation of spring cereals. Common species of insect predators and fungal pathogens occupy its primary and secondary niches. *Aphidius* nr *uzbekistanicus* Luzhetzki and *A. ervi* Haliday (Hymenoptera: Aphidiidae) have been reared from *S. miscanthi* in Australia and can be considered potential parasites of *M. dirhodum*.

The arrival of *M. dirhodum* in Australia has been expected, especially since its establishment in New Zealand. Its discovery in eastern coastal Australia tempts speculation that it flew/was blown across the Tasman sea, but the possibility also exists that it entered Australia on its primary host. Cut flowers, especially roses, are currently a flourishing import; they are regularly flown to Australia from Holland, South America, New Zealand and elsewhere (R. Paton pers. comm.). Several aphid species, including *Aphis fabae* Scopoli, have recently been intercepted by Australian quarantine authorities on imported roses.

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[*Manuscript received* 20 *July* 1984.]

Greenslade, P. and Ireson, J.E. 1986, Collembola of the southern Australian culture steppe and urban environments: A review of their pest status and key to identification. J. Aust. ent. Soc. 25: 273-291

BOOK REVIEW

Neurobiology of Arachnids. F. G. Barth (Ed.). Springer-Verlag: Berlin. 1985. xi + 385. DM 198.

This latest contribution to arachnid biology brings together the wide range of subject matter covered by the term neurobiology. For the most part the editor has chosen the contributors well and this has resulted in a comprehensive and well written English text with a coherent layout. The volume makes clear the sparsity of research on arachnids while opening to ones gaze those attributes unique to arachnids and on which exciting research is focused.

Of the 18 contributors, 13 are entirely or mainly about 1 class of arachnids, mostly spiders (10) or scorpions (3), as they are the most studied arachnids other than mites. The latter are barely mentioned as befits a traditional, but irrational, interpretation that mites (being the subject mostly of applied research and really honorary insects?) are not appropriate subjects for arachnologists! Although 8 of the chapters are from the Federal Republic of Germany this does not denote parochialism in the editor but reflects the strong influence of that country in this field led by the editor's own research. Other countries are represented as appropriate with 2 contributions from both the U.S.A. and Switzerland and 1 each from Australia, France, Great Britain, India, Japan and New Zealand.

The book is divided into 5 sections: I—The Central Nervous System: Structure and Development; II—Structure and Function of the Sensory Systems, which is subdivided into Vision, Mechano- and Chemoreception, and Sensory Nerves and Peripheral Synapses; III—Senses and Behavior; IV—The Motor System and V—Neurobiology of a Biological Clock.

As is often the case in books collated by an editor the volume falls to some extent between the categories of textbook and specialist papers. In some chapters the subject matter is well integrated and provides a useful introduction to the subject, covering the nature of the problem, the theoretical background and methods used to investigate the questions (IV—The morphology and optics of spiders' eyes (Land); IX—Slit sensilla and the measurement of cuticular strains (Barth)). A few papers seem misplaced (XVIII—Neurobiology of a circadian clock in the visual system of scorpions (Fleissner and Fleissner); XV—Analytical cybernetics of spider navigation (Mittelstaedt)), their justification being only the arachnid subjects but they are not integrative and would have been better presented in a more specialised volume.

The volume is up to date as attested by the large number of references cited from the year of publication. It is profusely illustrated with quality photographs and diagrams which, with their comprehensive captions, can mostly be understood without reference to the text despite the complexity of much of the subject matter.

I am left with a feeling of satisfaction with the book due to the excellence of much of the research presented and its manner of presentation. It will be essential reading to those interested in the comparative neurobiology of arthropods and, together with *Spider Communication* edited by Witt and Rovener (Princeton University, 1982), for those entomologists who need to know how the arachnids perceive their prey.

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